



AMSAT

**THE RADIO AMATEUR SATELLITE
CORPORATION**

PROCEEDINGS OF THE

AMSAT-NA

**37th Annual Space Symposium
and AMSAT-NA Annual Meeting**

October 18 - 20

2019

Arlington, Virginia



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First Edition

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Welcome to Washington, DC!

It is with great pleasure that I personally welcome you to the 2019 AMSAT Space Symposium and Annual Meeting. This is the 37th Symposium, reflecting a long tradition (started in the early 1980's) to provide an annual forum for amateur satellite enthusiasts to gather and share their ideas. AMSAT is proud of the technical content of the papers presented over the years reflecting the inventiveness of our volunteers and the significant contribution of presenters to "advancing the radio art." The word amateur comes from the Latin root "amare" meaning "to love". So amateur radio literally means to love the radio art, and the Radio Amateur Satellite Corporation means the Corporation of the lovers of the radio art with spacecraft. To celebrate the 50th Anniversary, this Symposium features two unique looks at the beginnings of AMSAT. First is OSCAR Park, where the ARRL has loaned AMSAT OSCAR-1, and also on display in Gallery III is a full size Phase 3A space frame, small sized AO-10 and AO-13 models, a working ARISSat-1, and the Fox-1 mock up. Second is the banquet speaker line-up featuring Lance Ginner, K6GSJ, builder of OSCAR-1, George Jacobs, W3ASK, who proposed a Project OSCAR for the east coast, Dr. Perry Klein, W3PK, the founding President of AMSAT, Dr. Owen Mace, builder of AO-5, Richard Tonkin, builder of AO-5, and Mr. Jan King, W3GEY, early AMSAT Project Manager and pioneer.

Holding our Symposium in the Washington, DC area this year is certainly fitting given that this frontier that was created by some of the above individuals, who had to forge new paths and create the new opportunities by forming AMSAT just across the Potomac River some fifty years ago. Likewise, AMSAT's pioneering innovation in small satellite design and applications for amateur radio and science continues to be well recognized. We expect our last Fox-1 class satellites to be in orbit within the next few months, this time with a linear transponder. RadFXSat-2/Fox-1E is part of the ELaNa-XX launch and features a new linear transponder now expected to fly in Fourth Quarter 2019.

There are other flight opportunities for AMSAT's comm package that are being developed. "An OSCAR in every university CubeSat" that further enhance amateur

radio's presence in space while supporting scientific payloads. The University of Washington's HuskySat carries an AMSAT constructed linear transponder and is also scheduled to launch before the end of the year. AMSAT has signed partnerships with Virginia Tech, University of Colorado Boulder, and Vanderbilt. AMSAT is finalizing an agreement with Radio Amateurs of Canada (RAC) and is pursuing agreements with AMSAT-DL & AMSAT-UK.

Other AMSAT projects include ARISS (Amateur Radio on the International Space Station) IORS (Inter-Operable Radio System). The IORS should launch by summer of 2020. International cooperation is also developing with the Amateur Radio Experiment (AREx) for the Lunar Gateway mission.

The engineering work on the GOLF (Greater Orbit, Larger Footprint) 3U series of CubeSats continues, and GOLF-TEE is coming along nicely. The CubeSat Simulator for Educational outreach made its' debut at Hamvention this year and planning is in the works for an improved model.

Meanwhile, the 37th AMSAT Space Symposium provides an opportunity to discuss the above and our next generation of projects. ASCENT (Advanced Satellite Communications and Exploration of New Technology) development program continues to help our engineers to develop new technology. AMSAT has an agreement with an Industrial provider for up to 3 ADAC (Attitude Determination and Control) packages for the AMSAT-built GOLF HEO (Highly Elliptical Orbit) satellite and always exploring opportunities for a Geostationary ride should such an opportunity arise.

As is AMSAT's tradition, this edition of the Proceedings contains details about our satellite designs that we're placing in the public domain through formal publication. We're releasing these materials so that we may openly discuss our spacecraft development efforts in public, as well as, our desire to encourage greater use of amateur radio in space, and to provide a foundation for other institutions to utilize our design.

After fifty years, we continue to develop remarkable satellites with educational outreach and scientific benefit that provides the basis for fulfilling AMSAT's mission. That mission is celebrating its fiftieth year, so look for future events throughout next year. The future is space and AMSAT is there and will continue to be. Your support will help to ensure a bright future for lovers of the spacecraft radio art.

73,

A handwritten signature in black ink, reading "Joseph K. Spier" with "K6WAO" written below it.

Joseph K. Spier, K6WAO, President



Dr Owen K Garriot, W5LFL, passed away on April 15 at his home in Huntsville, AL, at the age of 88.

As a young boy growing up in Oklahoma, Owen went with his father to a meeting of the local amateur radio club, sparking a lifelong interest in radio and electronics that eventually led him to the University of Oklahoma, the US Navy and Stanford University, where he taught electronics, electromagnetic theory, and ionospheric physics as an assistant professor. After obtaining his PhD from Stanford he performed research in ionospheric physics and authored or co-authored more than 45 scientific papers.

Owen was selected as a scientist-astronaut by NASA in June 1965. He served as a CapCom during the Apollo 11 mission, making him one of a very small number of people who spoke directly with Armstrong and Aldrin during the time that they were on the lunar surface, and he was quite possibly in line to visit the moon himself if the last three Apollo missions had not been canceled.

His first space flight was on the Skylab-3 mission from July 28 to September 25, 1973. On this record breaking 59 day mission, Owen spent many hours operating Skylab's Apollo Telescope Mount, contributing vital data on the newly discovered phenomenon of Solar Coronal Mass Ejections, which are an important part of what is now called Space Weather. He also spent 13 hours and 43 minutes in three separate extravehicular activities outside the orbital workshop. During the mission Owen pulled a prank on mission control in Houston by playing the recorded voice of his wife on the air-to-ground loop, pretending to be a stowaway on the spacecraft.

Prior to his flight on Skylab, AMSAT submitted a proposal to NASA called SKYLARC (Skylab Amateur Radio Communications), but permission to operate an amateur radio station from Skylab could not be obtained in time for the mission. That would have to wait another decade, when Owen was selected to fly as a mission specialist on the STS-9/Spacelab-1 mission aboard the Space Shuttle Columbia on November 28, 1983.

It was during that ten day mission that W5LFL thrilled radio amateurs around the world by making the first ham radio contacts from space. Thousands of hams listened on 2-meter FM, hoping to hear him or to make a contact. No special provisions were made on board the spacecraft in terms of equipment, Owen simply used a hand-held 2-meter FM transceiver operating on battery power with its antenna in one of Columbia's aft flight deck windows. His first pass was down the US West Coast. "As I approached the US, I began to hear stations that were trying to reach me, on my very first CQ, there were plenty of stations responding." His first contact was with Lance Collister, WA1JXN, in Montana.

W5LFL ended up working stations around the globe, among them such notables as King Hussein, JY1, of Jordan, and US Senator Barry Goldwater, K7UGA. "I managed to do it in my off-duty hours, and it was a pleasure to get involved in it and to talk with people who are as interested in space as the 100,000 hams on the ground seemed to be. So, it was just a pleasant experience, the hamming in particular, all the way around."

From 1984 to 1986, Owen held the position of Project Scientist in the Space Station Project Office. In this position he worked closely with the external scientific communities and advised the Project Manager concerning the scientific suitability of the Space Station design. Owen was preparing for another space shuttle flight on the first Environmental Observation Mission (EOM-1) in 1986 but this mission was canceled following the loss of the Space Shuttle Challenger in January of that year. He resigned from NASA in 1986 and later served as Vice President of Space Programs for Teledyne Brown Engineering in Huntsville, AL. This division provided payload integration for all Spacelab projects at the Marshall Space Flight Center and had a substantial role in the development of the U.S. Destiny Laboratory for the International Space Station.

He devoted additional time to several charitable activities in his home town, including the Enid Oklahoma Arts and Sciences Foundation of which he was a co-founder. In 1992 he accepted a position as Adjunct Professor in the Laboratory for Structural Biology at the University of Alabama in Huntsville and participated in research activities there involving new microbes found in extreme environments such as very alkaline lakes and deep sea hydrothermal vents. Hyperthermophiles were returned from several dives in Russian MIR submersibles to the Rainbow Vents at a depth of 2,300 meters near the Azores in the Atlantic Ocean. Other research activities included three trips to Antarctica from which 20 meteorites were returned for laboratory study. He was also a co-founder and President of Immutherapeutics, Inc. in Huntsville.

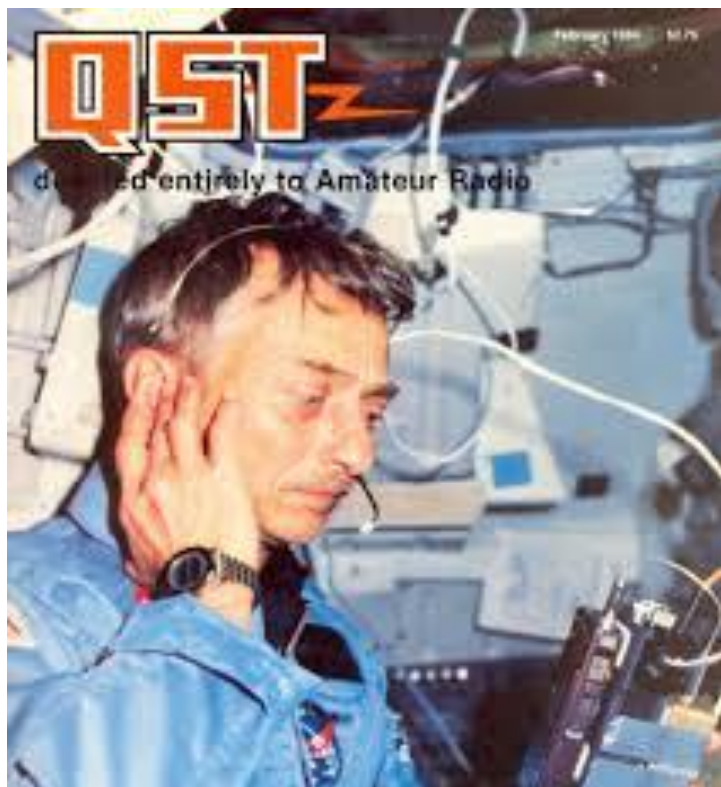
In 2002 Owen shared a Dayton Hamvention Special Achievement Award with fellow amateur radio astronaut Tony England, W0ORE.

Owen was co-author, with fellow astronaut Joseph Kerwin and writer David Hitt, of *Homesteading Space: The Skylab Story*, a history of the Skylab program, published in 2008. He was co-author of *Introduction to Ionospheric Physics* with Henry Rishbeth and was a contributor to the book *NASA's Scientist-Astronauts* by David Shayler and Colin Burgess.

Owen's son Richard Garriott, W5KWQ, was a private space traveler to the International Space Station in 2008, flown there by the Russian Federal Space Agency. This flight made Owen and Richard the first American father and son astronaut pair. Richard also made ham radio QSO's during his space mission using amateur radio gear that was permanently installed on the ISS, made possible in large part by Owen's pioneering work that led to the establishment of the SAREX and ARISS programs and the continuous and permanent presence of amateur radio on NASA manned space missions.

Owen is survived by his wife Evelyn (Eve) Garriott and four children from a previous marriage: Randall, Robert, Richard, and Linda.

By Dan Schultz N8FGV with inputs from AMSAT, ARRL, NASA, IEEE, AGU





It is with great sadness that we announce the passing of ARISS team member Keith Pugh, W5IU. Keith spent his life on Earth as a true gentlemen serving others, enjoying friendship and relationships, and supporting his passions...amateur radio, flying and most importantly his love of God and all the great things on this Earth.

Those that knew Keith considered him a Texan through and through. But truth be told, he was born and raised in Dodge City, Kansas. After college, he left Kansas and settled permanently in the Fort Worth, Texas area where picked up that Texas accent and welcomed us into his world. And it is in Texas where he passed away on May 24, 2019.

Active with AMSAT and Amateur Radio satellites since the 1980's, Keith jump-started his passion for amateur radio on human spaceflight missions in 1991, when the Space Station Mir was in orbit and Soviet ham radio operators were talking to the world-wide amateur radio community. Keith helped install a Soviet Space Exhibit in Fort Worth in 1991 and he hosted Musa Manarov U2MIR's visit to the USA. Ultimately, Keith joined the ARISS team in 2004, where he has provided support as one of our operations leaders, technical mentoring numerous schools and ARISS contact organizations and providing his warm friendship and guidance to all in our team. Keith also attended several of our ARISS International meetings, including our 2008 ARISS-I meeting in Moscow and Kaluga.

Many of us were aware of Keith's cancer. But, Keith being Keith, he kept most of his pain and suffering to himself. He remained joyful and humble until his death. In fact, just a few days before his death--this past Tuesday, Keith signed into the ARISS International teleconference, apologizing that he came in late. None of us knew this would be our last dialog with such a close friend and outstanding member of our team.

As I stated, one of Keith's passions was flying as a private pilot. In fact for one of his vacations he flew a Cessna aircraft around Australia. As a fellow pilot, I know that Keith must have been an avid fan of the poem "High Flight" written by John Gillespie Magee Jr. Paraphrasing this poem:

While we mourn the loss of our good friend, Keith Pugh, let us joyfully
reflect on the fact that Keith has
Slipped the surly bonds of Earth
And danced the skies on laughter-silvered wings;
Topped the windswept heights with easy grace
And, while with silent lifting mind, Keith has trod
The high unsurpassed sanctity of Space,
Put out his hand and touched the face of God.

Our thoughts and prayers are with Keith Pugh, W5IU SK as he touches the face of God.

73, Frank Bauer, KA3HDO

Designing the First Satellite Built in Australia

Richard Tonkin and Owen Mace

Introduction

Three boys, two continents and a spot of light. Little did Richard, Jan and Owen know how that spot of light moving slowly cross the sky would determine their lives.

The spot of light was, of course, the first artificial earth satellite, Sputnik 1, launched by the Soviet Union in October 1957. Among other things, it lit up the imagination of those boys who became space nuts soaking up every bit of information about satellites, space, rockets and astronomy. Not that there was much serious information as this was the height of the competition between the Soviet Union and the USA – the Cold War.

Less than a decade later Richard and Owen met when they joined the Melbourne University Astronautical Society. With other members, the squeaks and whistles of many satellites, including one bound for the moon, were received on our home made quad helix antenna and an ex-war time receiver. We supplied weather pictures from TIROS satellites to the Bureau of Meteorology (Australia's approximate equivalent of the National Oceanographic and Atmospheric Administration, NOAA) for some 18 months before it got its own equipment. I still remember being told that pictures of clouds from space would never help weather forecasting!

Then one day - both Richard and Owen claim responsibility – the idea of building our own satellite was suggested. Since there was no one in Australia who had built a satellite, there was no one to tell us that it was not possible.

So we did.



Preparations

The first task was the most important – what was our satellite to be called? After much discussion we settled on *Australis*, signifying our huge, southern country.

Next, who would launch Australis? There were no launch sites nor launch rockets in Australia, so our thoughts turned overseas. The baddy, the Soviet Union, was out of the question but our side, the United States, had already launched three amateur radio satellites, so there was our possible launch. To confirm that we could get a launch, a letter was air mailed to Project OSCAR on the West Coast, would they launch our satellite? A reply came back, very promptly, they would *try* to launch our satellite. That was good enough for us.

Now, what are we going to build?

The Mission

First, Project OSCAR suggested a satellite size of around the dimensions of their forthcoming OSCAR 4 satellite, approximately 50 x 30 x 20 cm (22 x 12 x 8 inches).

We quickly realised that, for a number of good reasons, an amateur radio satellite was the ideal goal. Not only were the three previous OSCAR satellites built by and for amateurs, it also solved the question of what radio frequency we would use. The two metre amateur band, as OSCAR had used. There was another advantage, too. There was no need for approval by the Australian spectrum management people as our satellite would be a mobile station of one of our members! Regulators off our back.

Now the question was, what do we want our satellite to *do*? (Just the sort of question a bunch a nerdy, somewhat asberger-syndrome affected boys would ask.) The answer was obvious – a two metre to two metre linear translator. Quickly, those who understood these things – Richard was a law student and Owen in the first year of his electronics degree – realised that this would be very difficult. The issue, of course, was filtering sufficiently so that the transmissions would not de-sensitise the receiver to such an extent that it would be incapable of receiving anything. The only reasonable solution in those days was a cavity resonator and a good one at that. Half a wavelength at two metres is one metre, which is much bigger than the agreed size for Australis. We also realised that changes in size due to temperature changes in space might seriously compromise the performance of the resonator. And we had no idea what those temperatures might be – recall that no one in Australia had any experience with satellites then.

A channelised frequency modulated signal might be an alternative but it would also require very effective filtering.

Finally, it was decided that we would focus on a fundamental issue for satellite communications, namely orienting the antennas to optimise signals. We also decided that we would investigate longer range communications with a ten metre transmission. So there was our mission definition – simple satellite, but not so simple for us.

Orientation and Stabilisation System

Any satellite transmitting or receiving radio signals should have a reasonably steady signal at the receiver to avoid “fades” where data is lost or compromised. This is as true today as it was in Australis’ time.

We had no idea what the rate of rotation of Australis might be. Launch rockets typically rotate about their longitudinal axis to help stabilise the direction that they are pointed. Also, when Australis was ejected from the launch rocket, any imbalance in the ejection springs would add a further rotation, about a different axis. We had to live with the notion that Australis would be spinning when placed in orbit at a rate of perhaps a rotation every few seconds. It scarcely needs saying that this uncertainty made the design of a stabilisation system and prediction of its performance difficult at best. Furthermore, at the time we had only a vague understanding of the likely mechanical properties of the satellite.

We understood that large satellites were stabilised and oriented in three directions using a complex set of sensors, reaction wheels and gas jets. This was out of the question for Australis, if for no other reason than we simply could not afford the electrical power necessary to run such a system. No, the stabilisation system had to consume minimal electrical power, or ideally none. Fortunately, Owen and

his colleague, Steve, who had been press-ganged into the Australis project, were electrical engineering students and had recently learned some of the physics of magnetism and magnetic hysteresis. Equally fortunately for Australis (and indeed for all of us earthlings) the Earth has a magnetic field and this afforded us a means of crudely stabilising and orienting the satellite.

There are, therefore, two parts to the subsystem – a means of reducing any residual spin of our satellite as it enters orbit and a means of orienting it in a direction suitable for the antennas. The sub-system was called the Magnetic Attitude Stabilisation System, MASS, consisting of orientation and stabilisation components.

Stabilisation Component

When magnetic materials are subject to changing magnetic fields, energy is absorbed by the material as the atoms (or rather the magnetic fields of the atoms) within the material are re-oriented by changes in the magnetic field. In some materials, used for electrical transformers for example, this energy is small but in others much larger. Could a material with a sufficiently large “hysteresis loop”, as it is known technically, absorb the rotational energy of Australis? The size of the hysteresis loop is a measure of the energy absorbed by the magnetic material for each reversal of the magnetic field, so a large hysteresis loop, absorbing a relatively large amount of energy, is desirable for this task.

After consulting some technical books in the University’s library, Steve reckoned that it might just be possible to reduce any satellite spin to a reasonable value in a few weeks. Any spinning or rotating could never be totally eliminated because, as the speed of the spinning was reduced, so the number of magnetic field reversals, and the rate of absorbing rotational energy drops. Nevertheless, reducing the rate to, say, one rotation or fade per minute would make communication far more feasible.

Eddy currents in Australis’ aluminium skin due to the changing Earth’s magnetic field as the satellite rotated would also absorb energy and contribute to reducing the spin. We were unable to calculate the likely contribution of this mechanism.

We found an alloy consisting of about 50 per cent iron and 50 per cent nickel with a very high hysteresis loop. We could buy it at a cost of US\$35 plus costs for the freight and customs clearance. This was one of the few parts of Australis that were not donated and we had to buy!

There was one further problem, however. The material had to be annealed in a dry hydrogen atmosphere at 2150°F for 2-4 hours, followed by a furnace cool at 100-200°F per hour down to 800°F to achieve the desirable properties. Finding someone willing to heat hydrogen to high temperatures would be a challenge! Nevertheless, that brave someone was found at Monash University in Melbourne and the wires were duly soaked in a hot hydrogen atmosphere for the due time and allowed to cool at the due rate. The challenges of building a satellite! (Recently Fate in the form of rabbits brought together Owen and the student who built that furnace!)

Following the annealing, there was a memorable afternoon as Steve and I set off to the student’s electronics laboratory in the Engineering Faculty at Melbourne University to make the measurement of the hysteresis loop. Arriving at the laboratory with the material in the form of wires about 3mm diameter, an irate and insistent lecturer demanded that I not enter wearing flip flops – imagine the danger present when measuring a magnetic hysteresis loop when wearing thongs! (The voltages were low.) Nevertheless, the rules were the rules and I trudged off to change into something more to his liking, and in accordance with the rules. Eventually, the hysteresis loop was displayed on an

oscilloscope and the numbers recorded and analysed. This is not a difficult measurement to make (I've done it a few times since) but it was a novelty then, and a satisfying one, when done for the first time.

The upshot was that, yes, with a handful of these wires, the likely spin of the imagined Australis could be reduced to a reasonable value in a reasonable time. With all the unknowns, any quantitative analysis and estimate of the spin-down time was guesswork, but it did work.

After all this challenging and very interesting experience, we had our stabilisation system – a bundle of innocuous wires. Better than any lecture or practical class at University, we learned and thoroughly understood the principles of magnetic materials and hysteresis loops.

Significantly and most importantly, the wires required no electrical power for them to do their job; they were passive.

The ideal orientation system would orient Australis in a fixed direction relative to the Earth, so that the various antennas could be arranged to maximise signals towards the Earth. As we've seen, an active orientation system was utterly impractical for us. We needed another passive system and, once again, the Earth's magnetic field offered the solution.

As any child knows, two magnets attract and align themselves. The Earth's field is one of those magnets, so all we had to do was to place a magnet in Australis and, hey presto, Australis would be aligned with the Earth's magnetic field. Since the Earth's field is very roughly parallel with the Earth's surface over much of the populated regions (but not at the poles), here was an easy solution.

Not quite so quickly. How big a magnet is required to follow the earth's magnetic field, especially given that the field dips down at the Earth's poles and a satellite tends to do a 180 degree tumble as it passes over each pole? Furthermore, we had introduced a permanent magnetic field which may affect the hysteresis of the stabilisation wires. These were serious considerations that had to be understood and dealt with. More delving into technical books dealing with magnetic fields and, in fact, much of the theory is contained in Physics and Mathematics that was well beyond our understanding at that stage of our University careers – vector calculus and the like. Nevertheless, Steve was able to convince himself that magnetic orientation was feasible.

A loud speaker company in Melbourne that manufactured audio loud speakers supplied us with magnets.

We called our system the Magnetic Attitude Stabilisation System (MASS).

The two metre antennas were mounted parallel to the axis of the magnet and within a few weeks Australis OSCAR 5, as it is known in orbit, had locked on to the earth's magnetic field and the 2 m signal was steady. Success. And the first time such a system had been used on an amateur satellite.

Radio Transmitters

There seemed to be little value to fly MASS without measuring its performance, so that dictated a telemetry system and we decided that a simple eight channel telemetry would suffice. The measurement channels were:

- 1: HI identification
- 2: Battery current drain
- 3: X axis horizon sensor
- 4: Battery voltage

- 5: Y axis horizon sensor
- 6: Internal temperature
- 7: Z axis horizon sensor
- 8: Skin temperature.

All channels measured the parameters by the frequency of an audio tone, while the distinctive HI in Morse code identified channel 1. Each channel was sampled for 6.5 seconds within a 52-second telemetry cycle. The audio frequencies ranged from 400 Hz to about 3 kHz.

The three horizon sensors were buried in tubes to restrict their view and shade them from extraneous light. This led to a concern for the potential for damage and destruction should a sensor see sunlight directly. A balance had to be struck between a reasonable field of view for the horizon sensors and a narrow field to reduce the risk of damage from the sun. This was a risk that we had to accept but no damage occurred during the flight.

Each of the two radio transmitters, one two metre the other ten metre, carried this telemetry.

But we foresaw a problem. Path loss considerations demanded that the ten metre transmitter be considerably higher power than the two metre transmitter; nominally 250 mW versus 50 mW. The ten metre transmitter would seriously reduce the lifetime of the battery powered satellite, so we decided that we would fly a command system so we could turn the ten metre transmitter on and off to conserve battery energy. That was yet another first for an amateur radio satellite but being first didn't concern us – if we even knew then.

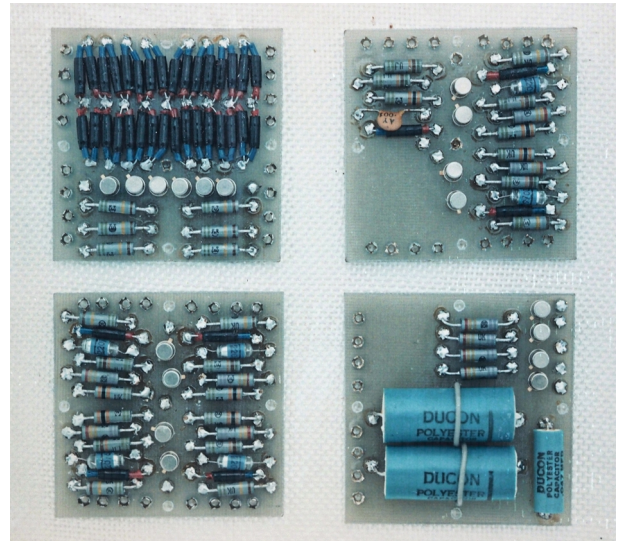
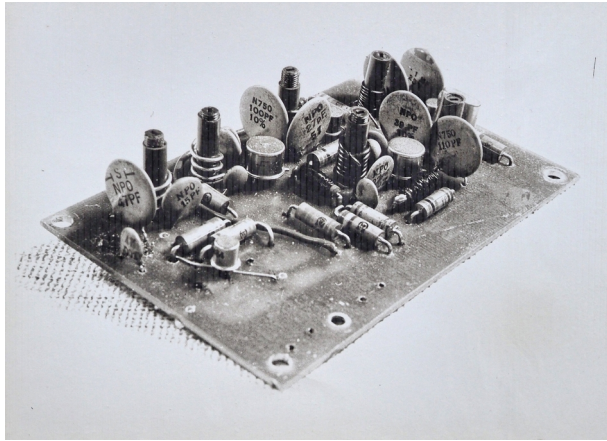
So now we had the system design for our Australis satellite, the components of which were:

1. Stabilisation system to reduce any residual tumbling in orbit.
2. Orientation system to ensure that Australis' antennas are in a direction favourable for receiving the signals on the ground with no, or minimal fading.
3. Two-metre, 50 mW transmitter, amplitude modulated by the telemetry signal.
4. Ten-metre, 250 mW transmitter, also amplitude modulated by the telemetry signal.
5. Command system consisting of a receiver and decoder to turn the ten-metre transmitter on and off.
6. Antennas for the two transmitters and the command receiver.
7. "HI keyer" to generate HI in Morse Code.
8. Telemetry system to generate the modulation signal for the two transmitters.
9. Battery to power the electronics.
10. Separation system to eject Australis from the launch rocket, including a master on/off switch
11. Mechanical structure, including thermal control which was outside our control and it was finally designed by NASA.

Without amateurs listening to Australis and reporting the signals they received, the project was worthless, except perhaps as an ego trip for us students. Accordingly, a ground segment was recognised as consisting of:

12. A means of generating and distributing predictions for when and where to look for Australis.
13. Network of amateurs to receive and report the signals they heard.
14. Analysis centre to analyse reception reports from receiving stations.
15. Command stations to send command signals to control the HF transmitter

Although we did not express the design decisions in this way, this was a system design that clearly delineated Australis' components, functions and interfaces, even if it was not formally documented except perhaps in the User Manual published before the launch. Here are some of the electronics:



On the left is the 2 metre, VHF transmitter being constructed and on the right the HI keyer boards

Testing

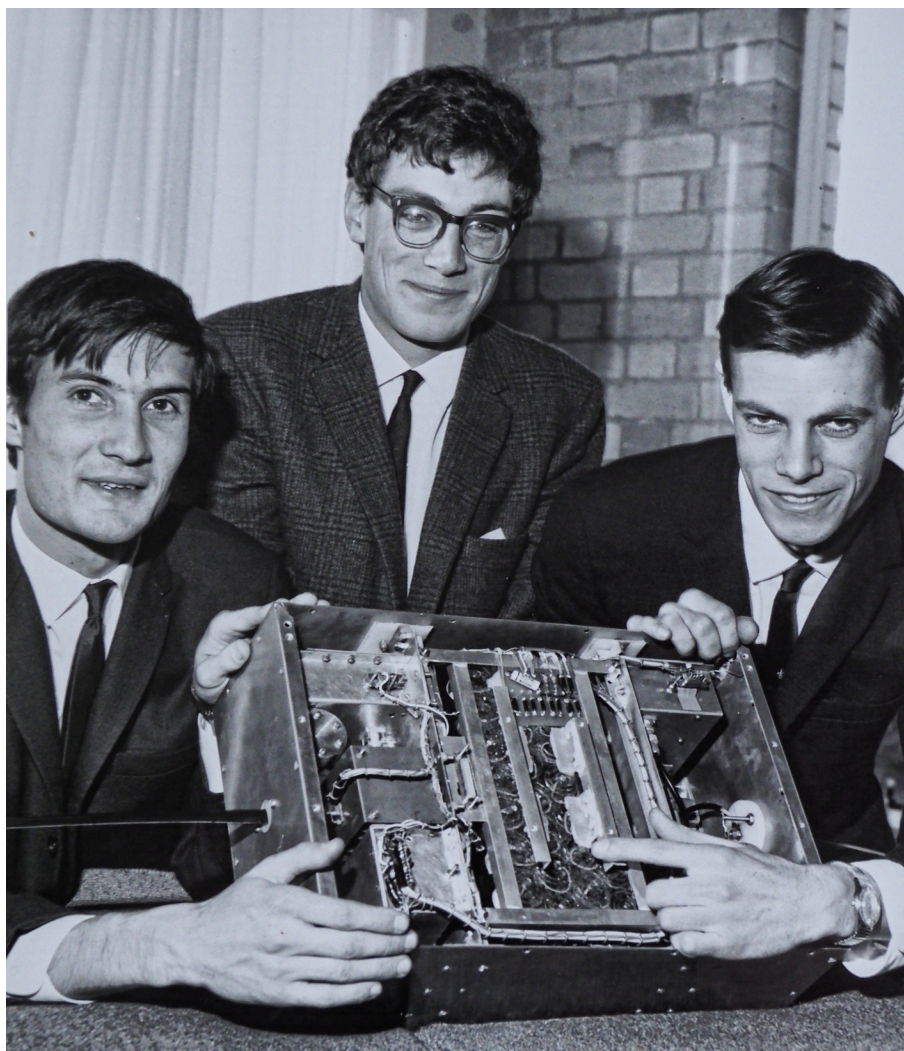
Of course we wanted to be sure that Australis had a chance of working once in orbit, so we needed to test the components and then the satellite as a whole in conditions that at least approximated those it would face in space. However, there were no available test chambers – no one had built a satellite in Australia before - so we had to improvise.

Richard worked part time for the Bureau of Meteorology and had access to weather balloons. What fun we had testing our sub-systems by flying them on weather balloons from the University – until, that is, the civil aviation authority suggested we should take our balloons well away from Melbourne's then international airport. Vacuum tests completed.

High temperature tests were conducted in Richard's home oven while his future wife objected that she was unable to cook dinner with that metal box in the oven. A large chest freezer in the Glaciology Department of the University was co-opted without the professor's knowledge, of course, for low temperature tests. Antennas tuned.

All good and ready for shipment.

This is how Australis looked before being shipped to California:



Owen, Richard and Paul with the completed Australis satellite in May 1967 before it was shipped to California. Batteries in the centre with electronics boxes either side. Antennas are flexible steel tape rulers. The magnet is not visible and the hysteresis rods are glued to the top cover.

Launch and Flight

Three of the team delivered Australis to Lance Ginner of Project OSCAR in San Francisco – Lance is here at the Symposium. Unfortunately, the US Air Force - understandably - decided that it could not launch an amateur satellite built by a bunch of mostly undergraduate students from a foreign (if friendly) country, so Australis lay in its delivery box in Lance's garage for nearly two years.

Then came the news that AMSAT had been formed and would fly our satellite! The third boy who saw that moving spot in the sky, Jan King, was put in charge of preparing Australis for flight. Jan and the first AMSAT president, Perry Klein, are both at this Symposium. Thanks Jan and thanks Perry, with whom Richard and I will have an eyeball QSO for the first time.

And fly Australis OSCAR 5, as it is known in orbit, we did. Can you imagine the excitement when we first heard our baby squeaking and beeping on 23rd January 1970? I still tear up when I hear the sounds of a very successful Australis OSCAR 5 in orbit.

Two audio files of the telemetry are included in the Symposium papers. Have a listen.

For a detailed report on the flight, see Jan King's article in the December 1970 edition of the QST magazine and the 9 February 1970 edition of Goddard News.

The firsts we achieved with AO5 were:

- First Australian-built satellite.
- First non-US amateur satellite.
- First University satellite.
- First non-government secondary payload launched by NASA.
- First amateur radio satellite launched by NASA.
- First satellite, along with Tiros M, to be launched by the then-new Delta N rocket.
- First 10-metre HF transmitter flown on an amateur satellite.
- First telemetry system flown on an amateur satellite.
- First command system flown on an amateur satellite. Commanding took some time to achieve thus shortening the life somewhat to about four weeks.
- First "PMASS" magnetic stabilisation and orientation system to stabilise and orient a satellite. There have been about 40 subsequent systems flown.
- First use of "Standard Orbits" method for predicting passes and for tracking. We understand that the method was later adopted and improved by NASA for use by US Antarctic expeditions.
- First time that satellite predictions (in this case equator crossings) had been transmitted directly from a computer to users via radio without human intervention.

There is a suggestion that Australis OSCAR 5 was among the early pioneers of small satellites launched from Vandenberg Air Force Base in California.

In addition, AO5 trained two groups, the Australians and the US AMSAT.

At the 23 July 2011 reunion of the group, the contribution of one of our group, Peter, to AMSAT with his command receivers was acknowledged: the AMSAT 7 command system continues to operate, along with the RTTY telemetry, after some 40 years since launch, and it is the longest surviving space command system ever. (He was advised not to use CMOS logic for his system as it was believed it would not survive.)

It was to be over eleven years before the Surrey University group under Professor Martin Sweeting flew the first of their small and relatively inexpensive satellites.

As it turned out, we were pioneers but not intentionally so. We were simply following our interests.

For more details, visit www.australis-oscar5.weebly.com where the Australis OSCAR 5 book can be bought.

What's New with Amateur Radio on the International Space Station: 2019 Edition

Frank H. Bauer, KA3HDO and Dave Taylor, W8AAS

The ARISS (Amateur Radio on the International Space Station) program began operations from ISS in December 2000, as the first payload activated by the first crew. To date, ARISS has held over 1270 contacts in 62 countries, providing over 500,000 students with direct exposure to ham radio and related lessons. Along the way, ARISS equipment has given thousands of hams access to astronauts and a space-based platform for communications.

Overview of the Preceding Year

ARISS is involved in many educational, outreach, and technical activities throughout the year, as well as providing opportunities for ham radio communications. Although ham radio volunteers support ARISS activities around the world, this paper concentrates on activities by the US team.

Educational Activities

ARISS strives to inspire, educate, and engage youth and communities in science, technology, engineering, arts, and mathematics (STEAM).

In the US, ARISS holds two proposal windows each year, in the spring and fall. During these windows, we accept proposals from US groups looking to host a contact and select those with the best education plans to move ahead for a contact. Each window includes webinars to provide information to prospective host groups.

US Education Team

Last year, ARISS formed an Education team to complement the Operations team. The 22 educators—all alumni of ARISS contacts—meet monthly with the mission of expanding ARISS educational outcomes and communicating the ARISS STEAM experience to other educators.

This year saw the introduction of Education Ambassadors, who will provide schools with educational guidance much as Technical Mentors assist schools on the operational side of a contact.

Other Education Team accomplishments include

- plans for an electronic space for sharing STEAM lesson ideas and resources among educators hosting a contact
- leading the proposal process for US contacts
- supporting development of a radio kit that can be distributed to ARISS schools

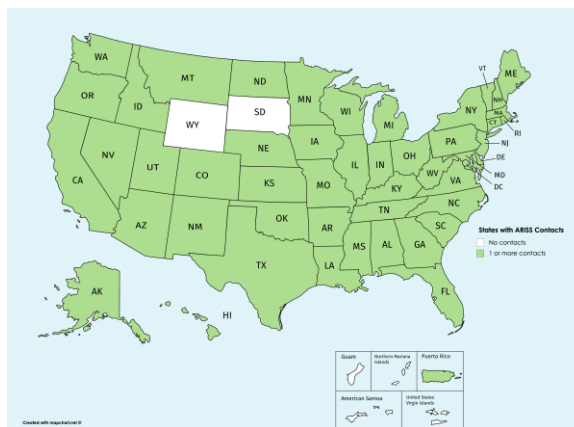
US Operations Team

The Operations team oversees contacts with ISS. The main activities of this team are guiding school's technical preparation and operating telebridge ground stations. In the past year, the Ops team has continued this work, holding weekly telecons to coordinate scheduling.

Astronaut Contacts

From October 1, 2018 to September 8, 2019, ARISS conducted 66 successful contacts in 20 countries. As usual, about 2/3 of these contacts used an on-site amateur radio station.

19 US contacts were held in 17 states. Since 2000, we have had contacts in 48 states, 1 territory (Puerto Rico), the District of Columbia, and Guantanamo Bay Naval Base.



US Contact Sites since 2000

South Dakota and Wyoming, we're looking for you!

Educational Outcomes

Talking to an astronaut is only part of what students gain when their school hosts an ARISS contact. The schools (or library, or summer camp, or...) execute a multi-faceted education plan leading up to the contact. Most include introductions to the hobby by hams from local clubs. In some cases, the equipment used for a contact becomes the foundation of a school ham radio club.

In addition, many schools add exciting extras to the lesson plans, such as:

- a visit from a local ex-astronaut (or maybe a current one)
- building hand-held antennas and tracking satellites with them
- building and programming robots
- building and launching model rockets
- building and tracking balloons with telemetry
- attending US Space Camp or a rocket launch
- visits to/from local space industries, such as space suit manufacturers and NASA engineers

Conferences

Members of the US Education and Operations teams presented papers, staffed exhibits, and sometimes both at numerous conferences:

- Space Exploration Educators Conference (Houston, Texas)
- Space Port Area Conference for Educators (Kennedy Space Center, Florida)
- ISS Research & Development Conference (Atlanta, Georgia)
- 3-D Printed Hab Challenge (Edwards, Illinois)
- Satellite Educators Conference (Los Angeles, California)

Recognition

MarconISSta, a PhD research project that shared the ARISS antennas for on-orbit spectrum analysis of amateur radio satellite bands, concluded in February 2019. Martin Buscher (the PhD student responsible for the project) presented two papers reporting results at the IAA Symposium on Small Satellites for Earth Observation. The MarconISSta was transferred to ARISS for future research.

NASA's annual report *ISS Benefits for Humanity* (April 2019) featured ARISS as one of the groups

providing education from ISS. Also included in the report were links to a NASA web page article about ARISS and an article on the MAI-75 experiments that use ham radio and SSTV.

SSTV Events

ARISS continues to hold special SSTV sessions from the Russian Zvezda module. These events use a Kenwood TM-D710E and a laptop running MMSSTV software. The ARISS events generally run continuously for 2-4 days over all parts of the world. The three events in the past year, with their themes:

- Feb 2019 – NASA on the Air
- Apr 2019 – Human Spaceflight
- Aug 2019 – Memorial to Owen Garriott

In addition, Moscow Aviation Institute conducted four MAI-75 propagation tests using SSTV in January, April, June, and July. These typically occur over Russia and are not audible in the US.

A team in Poland creates special diplomas (certificates) for each ARISS SSTV event. These are available to anyone who receives one or more images. You can request a diploma at <https://ariss.pzk.org.pl/sstv/>.

You can submit your received images and view many of the ones received by others at https://spaceflightsoftware.com/ARISS_SSTV/index.php.

Hardware Status

In the past, ARISS has operated one or two radio stations aboard ISS. Under our flight rules, our equipment is activated 24/7, except during EVAs and docking/undocking of visiting spacecraft. However, because most of our equipment was built prior to 2000, it is showing its age and we have had unpredictable down times in recent years. The digipeater has been particularly troublesome.

At this time, the digipeater (using an Ericsson HT and the original ARISS TNC) is frequently off, possibly due to an intermittent cable. A new TNC module flown in November 2019 failed to fix the problem. Because of limited engineering resources and the long lead times for replacing hardware, ARISS has since concentrated on getting the new radio system (IORS) ready to fly as soon as

possible. As described later in this report, we are nearly there.

SSTV operations use an unmodified Kenwood TM-D710E that belongs to the Moscow Aviation Institute (MAI), which flew it for experimental use. Because of problems with the Ericsson system, current voice operations also use this Kenwood radio.

International Meeting

As an international working group, ARISS is managed by Delegates from five world regions, corresponding to the five space agencies that contribute to ISS. In June, ARISS-International Delegates and other members of the ARISS team (37 people in all, from 11 countries) met at the Canadian Space Agency (CSA) headquarters outside Montreal.



Attendees at the ARISS-I meeting

Highlights of the meeting included

- a talk on CSA Gateway planning by CSA's Program Manager of the Lunar Gateway Program, Ken Podwalski
- discussions by the ARISS team on ideas for participating in NASA's Deep Space Gateway program, such as ham radio modes and bands, equipment development, education, and public outreach
- approaches for improving ARISS operations
- Dave Honess, M6DNT, ESA International Education Operations Coordinator, talked about ideas for enhanced ARISS education
- future SSTV sessions were discussed, including one to honor the late Owen Garriott, the first astronaut to use ham radio in space

During the meeting, JVC Kenwood engineer Shin Aota, JL1IBD, presented two ARISS IORS D-

710GA transceivers to ARISS-Russia. One radio will become the ham station in the ISS Zvezda module and one used for training cosmonauts.

Progress Toward the Future

The ARISS hardware and management team has been kept incredibly busy this past year dealing with multiple projects.

InterOperable Radio System (IORS)

The past four years have seen ARISS developing a new radio system for ISS to replace the aging equipment currently on board. This system has two components:

- A modified Kenwood TM-D710G transceiver
- An ARISS-built low-voltage power supply that can provide correct voltages for the D710G, Ham Video transmitter, VC-H1 SSTV unit, and future additional equipment

Both components will be certified for use anywhere aboard ISS. Two systems will be flown, one for the US operating segment and one for the Russian segment.



IORS Flight-Identical Test System

This year, the flight-identical unit was built and has been undergoing testing at NASA JSC. Minor problems were uncovered that have been fixed and two flight units now are under construction, with anticipated readiness for flight (after final NASA testing) by the end of 2019. For more details, see the *ARISS InterOperable Radio System* paper elsewhere in these Proceedings.

HamTV

Earlier this year, ARISS completed the negotiations and paperwork necessary to return the failed Ham Video transmitter to Earth for troubleshooting. It was returned by the Dragon spacecraft in January 2019 and in May reached Italy for evaluation by Kayser Italia, the company that built it. Because there is no funding for this effort, their engineers work on this between projects. Tests indicate that the modulator (MiniMod board) failed. A flight spare for this board is available; negotiations are underway regarding repair and retesting.

Dealing with Bartolomeo

About 3 years ago, ARISS learned of a plan to attach an external payload platform to the Columbus module. This platform, called Bartolomeo, would require the ARISS VHF/UHF antenna to be moved. ARISS managers and technical staff have had many meetings over the years to make plans, change them as the platform evolved, negotiate with ESA and Airbus, build a replacement antenna, and finally end up with a new agreement that keeps the existing antenna but with a new coax feedline. Still to be determined is whether ARISS will experience any interference from other antennas on the new platform (when it is finally installed).

Moving Out from Earth

NASA is looking outward to lunar orbit and the moon—and ham radio should go along. NASA and ESA both have asked ARISS to submit proposals for ham radio on Gateway. Plans are being made.

To learn more, see the paper *ARISS/AMSAT Gateway/Lunar Exploration Initiative* elsewhere in these Proceedings.

Making It All Happen

ARISS has all the needs and expenses of a for-profit business: people to make things happen, regular meetings (electronic and face-to-face) to keep a world-wide team in sync, hardware design and manufacture, and more. But this is ham radio and we are non-profit. Labor we've got, in the thousands of hours donated by our ham volunteers.

But everything else costs money and ARISS must raise it from donations.

Sponsors

ARISS is grateful to its continuing sponsors. Funds to provide full-time scheduling support at Johnson Spaceflight Center are provided by NASA's Space Communications and Navigation (SCaN) office and by the ISS U.S. National Laboratory (formerly known as CASIS). Support for day-to-day operations comes from AMSAT-NA and ARRL.

Fundraising

To raise funds to keep ARISS's work going, we are looking constantly for donations. We have created a challenge coin to encourage donors. We plan to solicit donations at contact venues, when we find a delicate way to do so.

In addition to these on-going efforts, ARISS conducted several special activities.

FundRazr

In October 2018, ARISS established a FundRazr.com page to raise funds for completion of the InterOperable Radio System. Included are many premiums, growing more desirable as donation levels increase.

Our FundRazr will be closing soon. If you have been putting off making a donation, there is still time to support ARISS and earn a premium. You can donate at <https://fundrazr.com> (if the link doesn't take you directly there, search for ARISS).

Auction

In April, ARISS conducted an online auction for two major items: a TS-890S radio signed by NASA astronauts (donated by JVC Kenwood) and a limited edition, multi-volume box set of the *2019 ARRL Handbook* (donated by ARRL).

ARDC Grant

While preparing for this year's Symposium, ARISS learned of a substantial (and unexpected) grant from the philanthropic arm of Amateur Radio Digital Communications (ARDC). This grant moves ARISS considerably closer to having the funds needed to complete all ten of the systems needed for training, engineering, and deployment.

Following ARISS

For up-to-date information about ARISS, including upcoming contacts, follow us at any (or all) of these media sites:

- ARISS website: <https://www.ariss.org/>
- Facebook: Amateur Radio on the International Space Station (ARISS)
- Twitter: @ARISS_status
- amsat-bb

To share information about ARISS with a teacher or other person interested in hosting an ARISS contact, direct them to this page on our website: <https://www.ariss.org/submit-a-contact-proposal.html>.

Details about submitting a US proposal are at <https://www.ariss.org/hosting-an-ariss-contact-in-the-us.html>.

ARISS Inter-Operable Radio System: Progress Toward Flight

Frank Bauer, Lou McFadin, Kerry Banke, Bob Bruninga, Bob Davis,
Ken Ernandes, Ed Krome, Kenneth Ransom, Gordon Scannell,
Mark Steiner, Dave Taylor

Introduction

The Amateur Radio on the International Space Station (ARISS) team hopes to fly the Inter-Operable Radio System (IORS) as a vital segment of the ARISS payload with elements flown on the ISS beginning in the year 2020. This equipment will be interfaced with other ARISS payload hardware and used on the International Space Station (ISS) to support the National Aeronautics and Space Administration (NASA) and other space agencies in space agency outreach, educational outreach, backup communication and experimentation. The ARISS IORS consists of a suite of amateur radio equipment and is designed to be employed in both the US Operating Segment and the Russian Operating Segment using either the 28 VDC or 120 VDC ISS power system. The IORS consists of a Kenwood D710GA amateur radio transceiver mounted to the Multi-Voltage Power Supply (MVPS), and the associated interconnecting cabling.

Objectives of upcoming changes to the ARISS equipment on the ISS will:

- Improve the Columbus Module downlink signal reception through a higher power transmitter.
- Enhance ARISS capabilities for educational contacts, every-day amateur use, and ISS backup communications
- Develop a standardized VHF/UHF radio and power supply system that will be inter-operable across all ISS Segments and modules including both the US and Russian segments.
- Certify, launch, install and operate a JVC Kenwood system with an ARISS/AMSAT-built inter-operable power supply and supporting cabling.

Mission Overview

ARISS is a long-running program using amateur radio equipment on board the ISS to involve students exchanging questions with astronauts on orbit. More than 1000 organizations have participated since the payload was first turned on in November 2000. Organizations include schools, museums, scouting events, and special events. It is also used to perform communications experiments with amateur radio operators on the ground. NASA's intent in having astronauts take part in ARISS is to involve the largest possible number of people, particularly youth, in Science, Technology, Engineering, Arts, and Math (STEAM) education in conjunction with the US, Russian, European, Canadian and Japanese space programs and through the help of amateur radio operators around the world. ARISS also serves an important function as a tertiary backup in the event of communications outages on the US and Russian sides.

Through ARISS, astronauts make scheduled and unscheduled Amateur Radio contacts with schools, random contacts with Amateur Radio operators, and contacts with astronauts' families. A few schools are selected from around the world for scheduled contacts with the ISS crew, after completing a comprehensive proposal that indicates a plan most consistent with ARISS educational goals. Scheduled contacts give the schools a 95% chance at achieving success. Ten or more students at each school ask the astronaut questions. The nature of these contacts embodies the primary ARISS goal of inspiring and educating students to pursue STEAM careers.

Progress Toward Flight Readiness

The IORS, under the leadership of Principal Investigator Frank Bauer, has made significant progress with an expectation of being declared flight ready near the end of calendar year 2019. The final testing (i.e., power quality and acoustic) of the IORS flight identical hardware was completed July 15. The Russian segment JVC Kenwood flight and training transceivers were delivered to Russian team member Sergey Samburov on July 27. All flight unit electronic boards have been populated and MVPS flight unit integration is in progress. The remaining tasks are listed in the flight readiness milestones below. Details of activities toward achieving these required steps are in the paragraphs following the milestones.

Milestones for Flight Readiness

The remaining flight readiness tasks are detailed below. Each of these steps are necessary as a precursor to being manifest on a launch vehicle:

- The Part 1 ARISS system and safety verification closeout is expected to be complete in October.
- The assembly and integration of the Columbus module flight unit is in progress and expected to be completed in early November.
- The IORS Flight unit testing at NASA Johnson Space Center (JSC) is expected to begin in early November. This will include abbreviated power quality and acoustic tests that will include bonding and grounding tests and relevant safety assessment testing.
- The Part 2 ARISS system and safety verification closeout is expected at the beginning of December.
- The ARISS IORS Phase 3 Safety Review is expected in mid-December.
- The ARISS IORS is expected to be declared flight ready by the end of 2019 or in early 2020.

MVPS Power Certification at Both 28/120 Volts

Electromagnetic Interference / Electromagnetic (EMI/EMC) tests were performed at JSC in July 2019. The Kenwood D710GA and MVPS were found to be compliant with the NASA JSC standards, specifically those found in SSP 57000 EMI requirements for CS01, CS01, and CS06.



Figure 1, EMI Test Configuration

The EMI test configuration is shown in figure 1. Figure 2 is an excerpt of the EMI test results.

TABLE 4.1: SSP 57000					
EMI TEST	DESCRIPTION	Input Power	Configuration	COMPLY? Y/N	NOTE
CS01	30 Hz - 50 kHz, Power Leads	28Vdc	A	Y	Test
			B	Y	Test
CS02	50 kHz - 50 MHz, Power Leads	28Vdc	A	Y	Test
			B	Y	Test
CS01	30 Hz - 50 kHz, Power Leads	120Vdc	A	Y	Test
			B	Y	Test
CS02	50 kHz - 50 MHz, Power Leads	120Vdc	A	Y	Test
			B	Y	Test
CS06	Spike, Power Leads	28Vdc	A	Y	Test
			B	Y	Test
CS06	Spike, Power Leads	120Vdc	A	Y	Test
			B	Y	Test

Figure 2, Excerpt of IORS EMI Test Results

MVPS Acoustic Testing

The Acoustic testing performed at JSC was done with the MVPS configured for maximum fan speed which showed that the fan noise exceeded the permissible level for continuous operation and would be allowed for 8 hours/24 hours operation. NASA sent on-loan an Acoustic measurement setup to our ARISS team in San Diego for additional acoustic testing under simulated realistic operating conditions rather than the worst case tested at JSC. These results have been forwarded to JSC and we are waiting for analysis by NASA. After NASA's evaluation is complete, we may need to work out an operating schedule based on their analysis and the needs of ARISS.

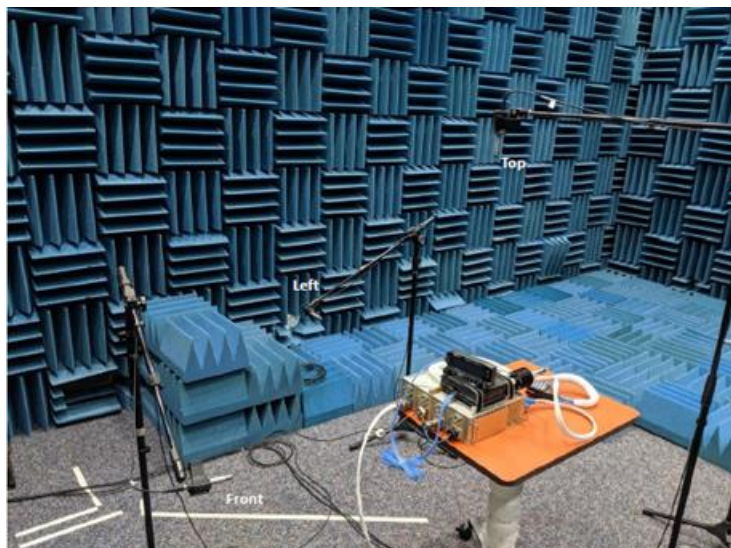


Figure 3, IORS Acoustic Test Configuration at JSC

Figure 3 is the IORS test configuration at JSC. Figure 4 is the acoustic measurement equipment loaned by NASA JSC for follow-on acoustic tests in San Diego.



Figure 4, NASA Acoustic Test Equipment

The data is taken at octave frequency intervals over a 20 second period. The San Diego tests were performed using voice, digital mode and repeater mode operation. Table 1 is an example of the San Diego data:

An Arduino was used to control the radio transmit function as follows:

- #1 Voice mode - 60 seconds on/90 seconds off tested after 10 minutes and 2 hours
- #2 Digital mode – 2 seconds on/2 seconds off tested after 2 hours
- #3 Repeater mode – 20 second on/1 second off/20 seconds on/50 seconds off tested after 2 hours

Table 1, Acoustic Test Results in ARISS San Diego Lab									
Test #	63	125	250	500	1000	2000	4000	8000	A
1	41.4	26.5	26.2	28	26.6	26.2	26.8	26	33.8
2	31.4	28.5	39.7	38.6	38.4	37.3	35.4	26.5	43.7
3	42.2	29.7	38.7	40.6	40	34.4	34.7	26.2	43.8
4	35.6	32.8	37.9	33.2	36.7	33.7	33.2	26.1	41
5									
6	40.9	27.5	38.3	37	37.9	34.5	34	26.2	42.2
7	41.7	27.2	38.3	37.2	41.1	35	34.3	26.2	43.8

Figure 5 shows the ISS-HAM IORS sound pressure levels during its loudest operation as tested at NASA JSC.

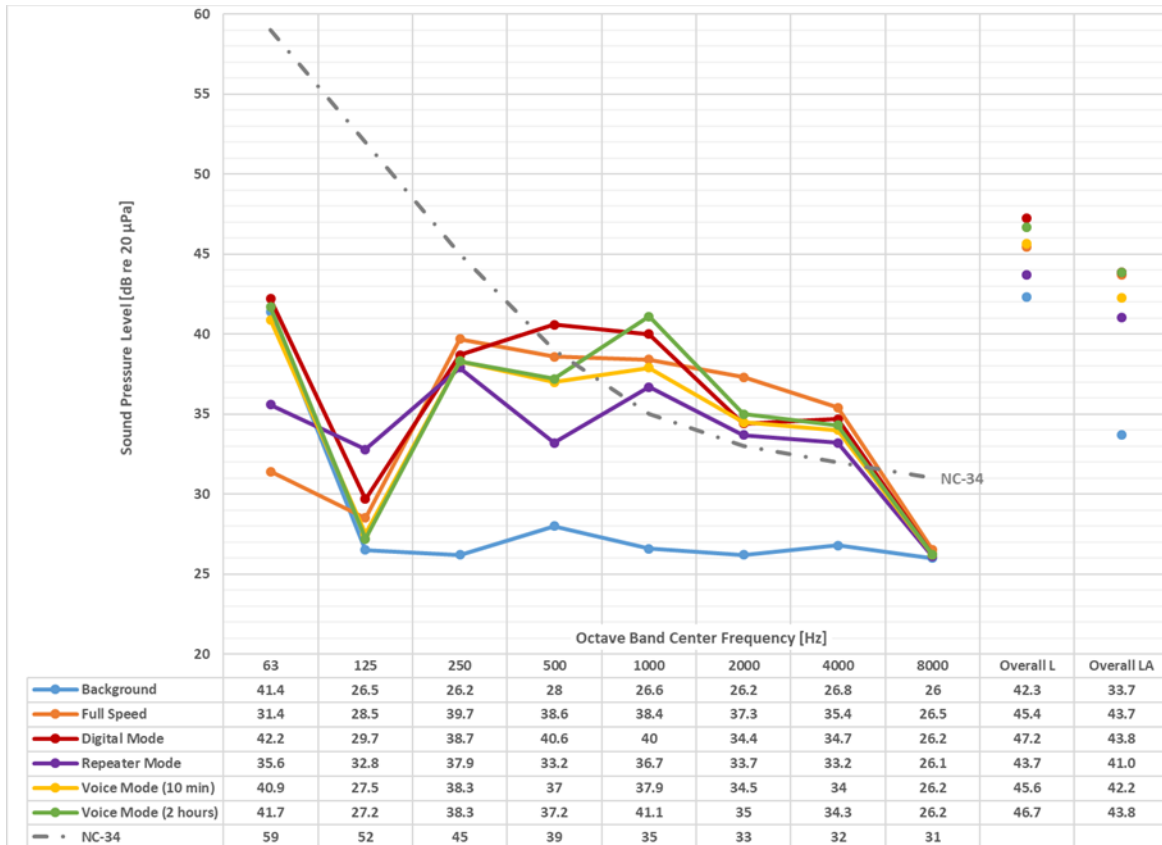


Figure 5, IORS Tested Worst Case Sound Pressure Levels

MVPS Touch Temperature Test

Early in the MVPS project, a series of tests were performed to ensure the selected cooling fans were adequate to meet the NASA temperature and acoustic noise requirements.

The touch temperature test ensures no externally-exposed MVPS surfaces can reach a temperature that could cause a burn or other injury to a crew member. The temperatures are measured after operating at the most extreme end of the normal operating conditions, including the Kenwood D710GA transmitting in a high duty cycle digital mode being the most severe. All transceiver operating modes are tested. The transceiver is mounted in the flight configuration on top of the MVPS as shown in figure 6, which also indicates the location of the temperature measurement sensors.

The NASA temperature standard for continuous human contact is a maximum of 45°C (or 113°F). However, since the MVPS has no external controls other than switches, a separate Hot Permissible Material Temperature (TPM) was computed for incidental and intentional contact of one second or less. The computed TPM for the MVPS was 72°C (or 161.6°F). The ARISS team nevertheless opted for the IORS hardware to be tested to the more stringent (i.e., cooler) 45°C standard.

The sensor locations and descriptions are as follows:

- “T1 SS fin” is a TMP36 solid state sensor clamped to the top center fin of the heatsink on the side opposite the fan air inlet. This is human-accessible touch temperature. It is always the second curve down from the top of the graph.
- “T1 TC int” is a type K thermocouple epoxied into a drilled recess near the above

referenced heatsink internal to the MVPS and not human-accessible. Signal is conditioned by an Adafruit AD8495 amplifier.

- “T4 SS fin” is TMP36 as above but in the fins of the heatsink on the same side as the fan inlet. This sensor is also human accessible.
- “T4 TC int” is a thermocouple internally mounted to the same heatsink as “T4 SS fin”.

OPTICAL TEMPERATURE SENSOR POSITIONS

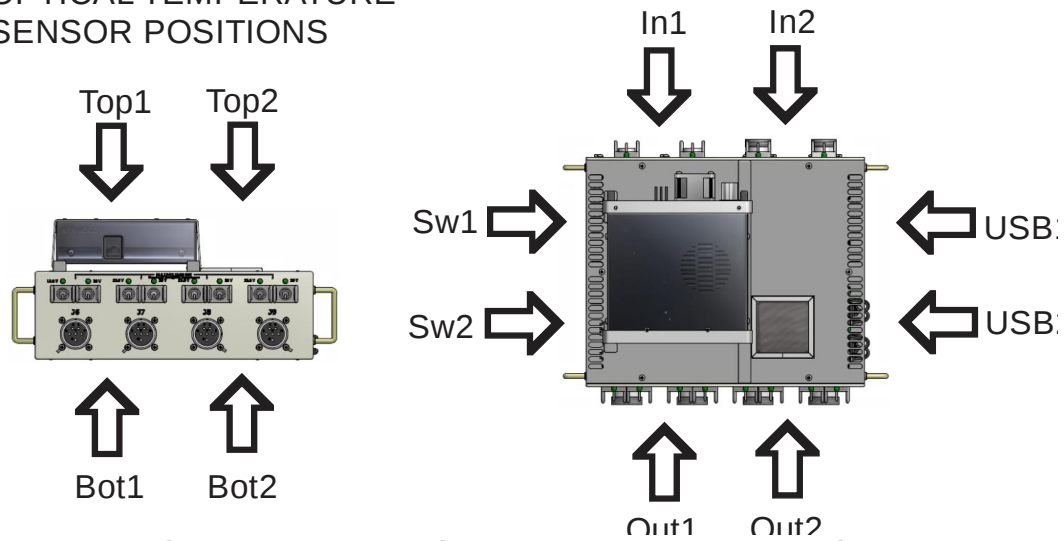


Figure 6, MVPS Touch Temperature Sensor Locations

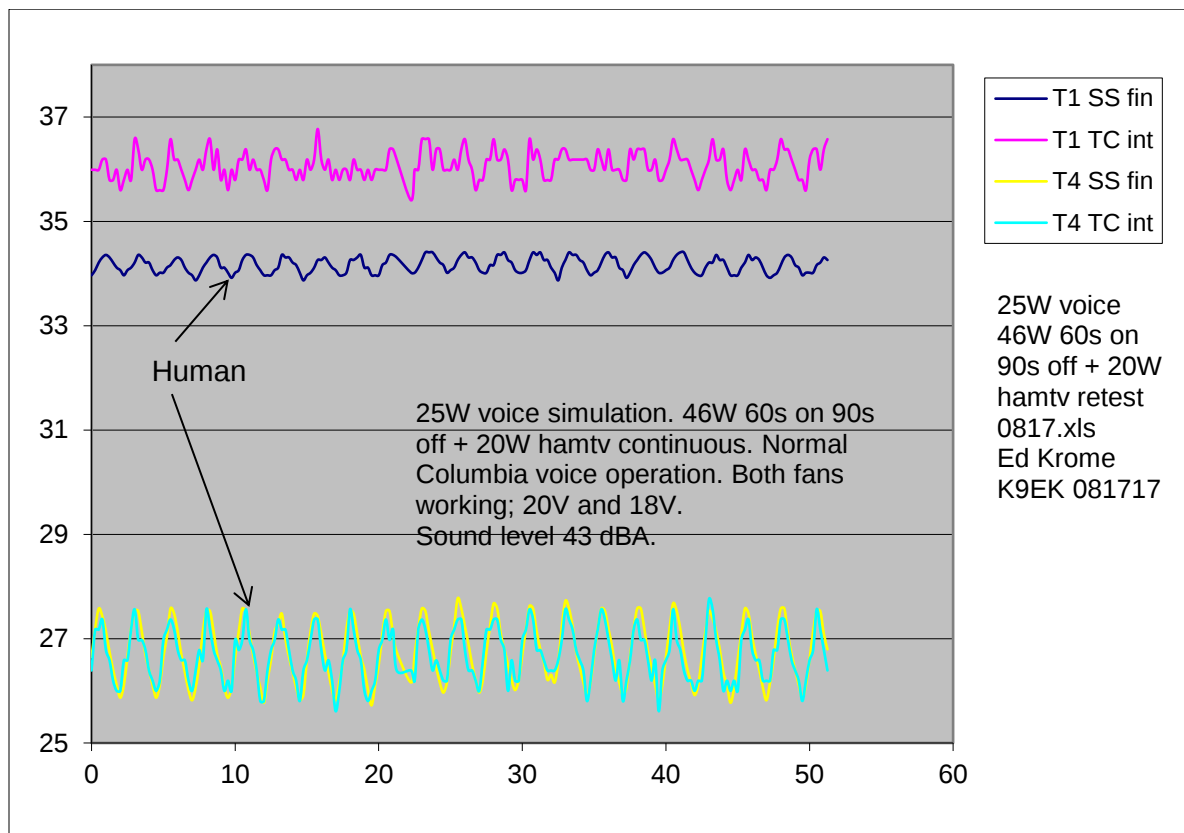


Figure 7, Temperature Results for the 25-Watt Voice Mode

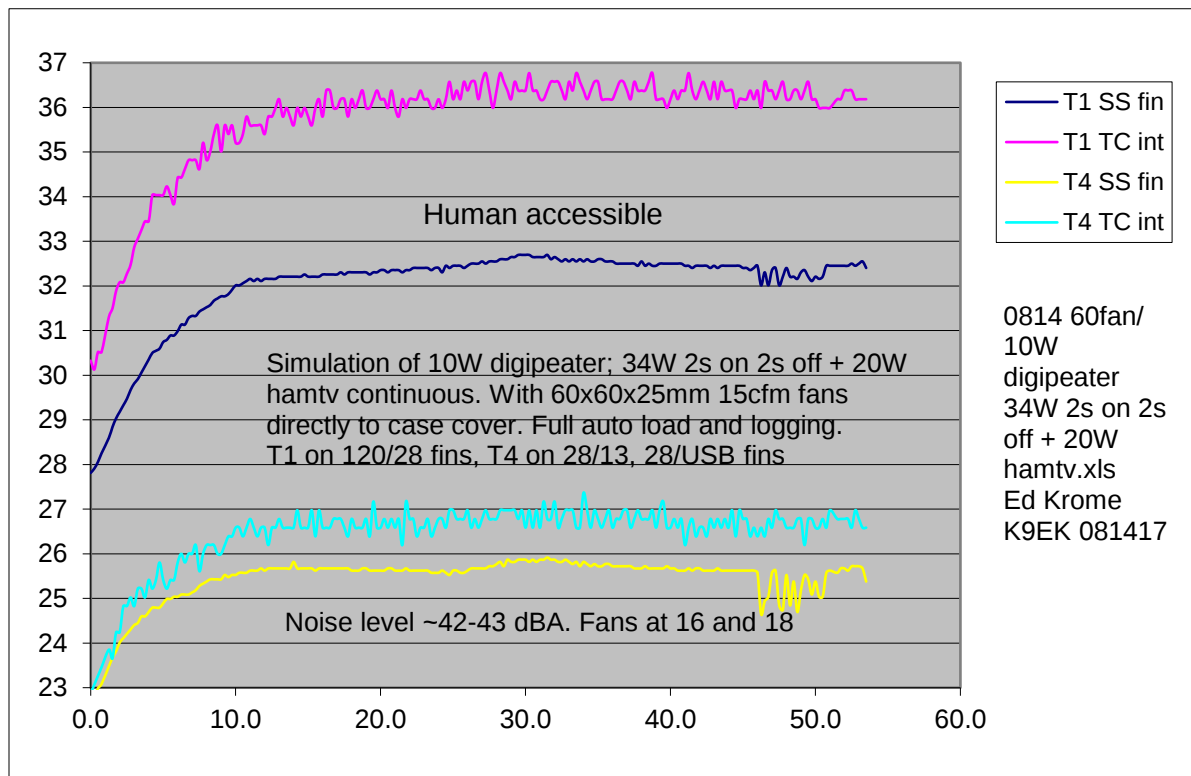


Figure 8, Temperature Results for the 10-Watt Digipeater Operation

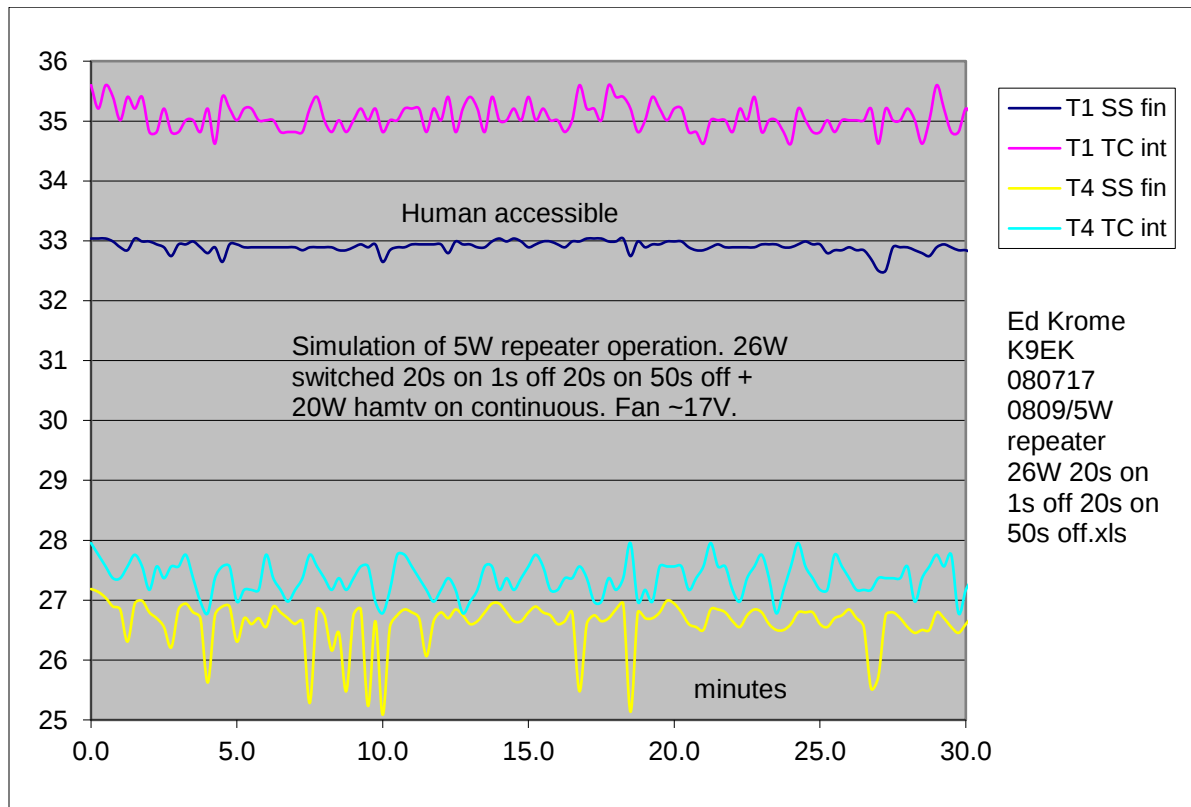


Figure 9, Temperature Results for the 5-Watt Repeater Operation

The touch temperature tests were performed both with loads cycled according to Kenwood D710GA published operating profiles and at a continuous load (i.e., “brick on key”) conditions. There are three Kenwood-defined loading profiles. These include the 25-watt voice, 10-watt digipeater, and 5-watt repeater operation. The MVPS temperatures remained well within acceptable levels for these tests.

Figures 7 through 9 are the plots of the temperature results. Specifically, figure 7 is provides the temperature results for the 25-watt voice mode, figure 8 provides the temperature results for the 10-watt digipeater mode, and figure 9 provides the temperature results for the 5-watt repeater operation.

Kenwood D710G Transceiver Firmware Programming

The transceivers were updated to the latest custom ARISS firmware from JVC Kenwood in April 2019, in preparation for testing at Johnson Space Center. Three units (S/N 1005, 1006, and 1008) were programmed by Dave Taylor, Kenneth Ransom, and Bob Bruninga during firmware development. Ken Ernandes programmed the remaining seven units in possession of ARISS Chief Engineer Lou McFadin. These included the two U.S. flight units (S/N 1001 and 1002) and the two Russian flight units (S/N 1003 and 1004). This is a relatively automatic process, though there is a manual selection to distinguish between the U.S. and Russian software configuration. Figure 10 shows the U.S Flight Unit #1 in the process of being programmed to the latest firmware version.



Figure 10, U.S. Flight Unit 1 Being Programmed

NEW INTER-OPERABLE RADIO SYSTEM (IORS) HARDWARE

The new IORS system enhancements include:

- Higher power downlink improves school contacts, SSTV downlink and APRS operations
- Improved audio during voice contacts
- Reduced system downtime through dedicated power supply

- More robust soft/firmware in radio system to prevent accidental programming and reduce repeater mode command steps
- Upgraded JVC Kenwood D710 fan supports continuous repeater mode operations
- Sharing of hardware resources across modules when failures occur
- Common operations and training across US and Russian segments
- Supports future system developments
- Support for additional radios and accessories

The new IORS equipment consists of a JVC Kenwood D710GA transceiver, a Multi-Voltage Power Supply (MVPS), and interconnecting cables. This hardware will be interfaced with some of the legacy ARISS equipment to transmit and receive through the legacy antenna systems. The intent is to have an inter-operable system with components that will be certified and can be operated anywhere on ISS, but specifically will be used in the two areas with ARISS legacy antennas: the US Columbus Module and the Russian Service Module. Interoperability provides the following advantages: it leverages existing ISS power cables, it can be moved between modules in the event of on-orbit failures, and it allows for common training and operations.

IORs Transceiver

The JVC Kenwood D710GA transceiver, shown in figure 10, is a spaceflight modified version of this commercially-available product. The key safety modifications to this transceiver are the reduction of the maximum radiated power from 50 W to 25 W (through a hardware design modification by JVC Kenwood) and installation of a more robust (higher volume) cooling fan to reduce thermal load.

IORs Power Supply

The MVPS is custom designed for the ARISS system, with Kerry Banke performing the electrical design and Bob Davis performing the mechanical design. Figure 11 is an MVPS block diagram. The MVPS is equipped with two (2) voltage inputs, supporting 28 VDC and 120 VDC ISS power systems. The MVPS includes four (4) multi-voltage outputs, plus four (4) Universal Serial Bus (USB) power ports. Figure 12 is a photograph of the flight identical MVPS with a Kenwood D710GA mounted in place. The transceiver is mounted via Velcro straps. There is one 120VDC input that supports USOS module use and one 28VDC input that supports RSOS module or USOS use. Each of the two inputs is equipped with a pass-through output in order allow further equipment to be powered from ISS power via the MVPS, without having to remove power connections to the MVPS. The MVPS includes an integrated mounting bracket that allows the Kenwood D710GA radio to be mounted directly to the power supply via Velcro straps.

IORs OPERATING MODES

This section provides a brief description of the ARISS operating modes with the new IORS equipment installed. This is generally presented from the perspective of the ground operator. Details and updated information will be provided on the ARISS web site: <https://www.ariss.org>.

Voice Contacts

The ARISS system will continue to support two-way FM voice contacts pre-scheduled for schools as well as random amateur contacts (25 Watts). The voice downlink frequency for random contacts is **145.80 MHz** (worldwide). The voice uplink frequency is **144.49 MHz** for ITU regions 2 and 3 (the Americas, Pacific, and Southern Asia) and **145.20 MHz** for ITU region 1 (Europe, Russia, and Africa). Amateurs are cautioned not to transmit on the ISS downlink frequency. The voice contacts are split mode so the crew listens on the uplink frequency and transmits on the downlink frequency. Thus, the crew will not hear operators transmitting on the downlink

frequency. The most this will accomplish is making such an operator unpopular with others monitoring the downlink and/or attempting contact.

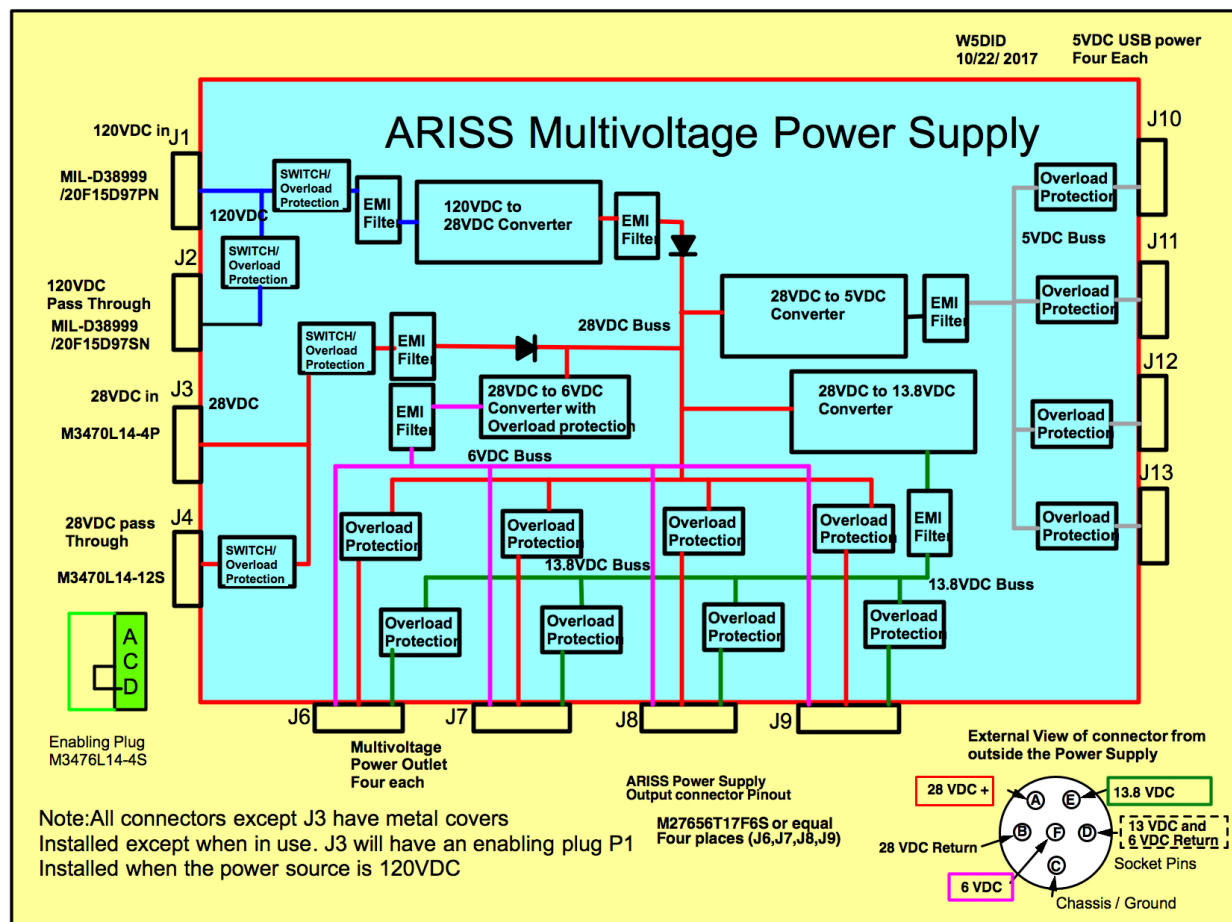


Figure 11, IORS Multi-Voltage Power Supply (MVPS)

Cross-Band Repeater Operations

The JVC Kenwood D710G transceiver is also capable of operating as a cross-band repeater (5 Watts). This operating mode will make the ISS an FM “easy sat” with an added bonus. The ISS crew will be able to join conversations occurring between ground stations in this repeater mode. The cross-band repeater capability was one of the drivers in the more robust thermal design in the D710GA.

The uplink frequency will be in the 145.990 MHz (67 Hz PL) and the downlink frequency will be in the 437.800 MHz.

Digital Communications

The IORS will have a packet digipeater. This will continue operations on the 145.825 simplex frequency, but will no longer support a BBS.



Figure 3 – MVPS and Kenwood Transceiver

Figure 12, MVPS with JVC Kenwood D710G Transceiver Mounted

Summary

The ARISS IORS has made significant progress toward flight-readiness. The flight-identical hardware has been through a rigorous set of testing to ensure compliance with NASA safety and operational suitability standards for human-occupied spacecraft. The flight hardware is currently being fabricated and will undergo an abbreviated set of tests to ensure it functions consistently with the flight-identical hardware. Following a successful system and safety verification closeout and final safety review the ARISS IORS is expected to be declared flight ready by the end of 2019 or in early 2020. The ARISS IORS team is pleased to be providing a new and highly-capable amateur radio station on board the ISS that will offer enhanced and exciting contact opportunities for both scheduled school contacts and general amateur use.

**Vermont Space Grant and Vermont NASA
EPSCoR Program
2019 Faculty Research Competition**

Deep Space Weak Signal Hardware and Software for CubeSats

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**Vermont Technical College
CubeSat Lab**

cubesatlab.org

1. Introduction

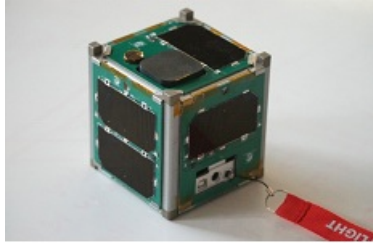
We, at the Vermont Technical College CubeSat Lab (cubesatlab.org) have been awarded the grant described here, which began, October 1, 2019.

With the coming availability of escape velocity launches for CubeSats, and high capacity ion drives (Busek BIT-3 [1]), it will soon be possible for universities to conduct deep space CubeSat missions. There are currently thirteen manifested on the SLS EM-1 mission [2]. For communication from far beyond low Earth orbit, current plans for the EM-1 6U CubeSats are to use the NASA Deep Space Network (DSN) [3]. The DSN has large dishes, up to 70m, which allow for high data rate communications from deep space. There are problems in that use is expensive at over \$6,000 per hour for the 70 m dish, and getting time is even more difficult.



70 m Dish at Goldstone, CA

We have been developing a complete software framework for CubeSats and other small satellites written in SPARK/Ada, called CubedOS [4]. Software is a major component in any modern spacecraft. In many spacecraft, it will require more effort than any other part of the spacecraft. In many cases, particularly in the CubeSat world, people are attracted to the hardware aspects of the spacecraft and leave the software to the end, are not familiar with modern software engineering practices and do a poor job in their software design and implementation. Most of the CubeSat experts believe that the majority of CubeSat failures (and there are a lot of failures) are software related. Large space projects in NASA or the European Space Agency put a lot of effort to try to have error free software. They don't always succeed, sometimes with catastrophic results. Modern software engineering uses techniques, language choice and specific tools to greatly increase the reliability of the software, and these techniques also reduce the effort required, thus reducing the cost of producing the software. At Vermont Tech, we are uniquely suited to high integrity software projects, as we have one of only three Software Engineering BS degree programs in New England (the others are at Boston University and Fairfield University.) We are also have an MS in Software Engineering. We used SPARK/Ada [5] (the language with the lowest error rate) for our first CubeSat, the Vermont Lunar CubeSat [6] launched November 19, 2013 and operational until burning up over the Pacific on November 21, 2015, having orbited the Earth 11,071 times for a distance of about 293,000,000 miles.



Vermont Lunar CubeSat



Our ORS-3 launch from Wallops Island.

Our basic CubedOS is on github [7], and currently two groups are using it for their CubeSat projects [8]. We are currently working on added deep space functionality to CubedOS, as no currently available software has it. We have added Spiral Thrusting, implementing an algorithm developed at NASA's Jet Propulsion Lab (JPL) [9]. This allows three axis angular momentum control with a two axis controlled thruster such as the Busek BIT-3, as the typical small satellite does not have room for auxiliary thrusters. We have a NASA Spacegrant Consortium grant starting this month to develop and test the weak radio signal protocol, JT-65 [10] and add it to CubedOS.

2. Project Objectives

The proposed work will address the current lack of deep space communication capability for small satellites without the use of the expensive and hard to schedule DSN. The development of the weak signal protocol, JT-65 and others, by Joe Taylor at Princeton, has made this work possible. (Dr. Taylor was a grad school professor of the PI, and undergraduate advisor to our NASA JPL supporter, Dr. Jay Goguen). He was the winner of the 1993 Nobel Prize in physics, and has expressed interest in following our work. Specifically, for this project, the proposed work has the following objectives:

- Take the current JT-65 software, designed for two human operators, and modify it to be controlled autonomously by our CubedOS software.
- Rewrite the critical portions of JT-65 in SPARK/Ada to greatly reduce possible errors.
- Test the software with a portable ground station and the Vermont Tech CubeSat Lab ground station using Moon bounce.

The proposed work is synergistic with topics outlined in the NASA Technology Roadmap [11]. In the Roadmap, among 14 identified technology areas, our proposed effort is tightly aligned with the following two aspects of Technology Area 5: Communications, Navigation, and Orbital Debris Tracking and Characterization Systems

TA 5.2: Radio Frequency Communications: "Radio Frequency (RF) Communications strives to dramatically accelerate techniques in use today for NASA's missions. RF technology development concentrates on getting more productivity out of the constrained spectrum bands that are allocated to space users. Although it is quite a bit more mature than optical communications, there is still a great deal of promise for

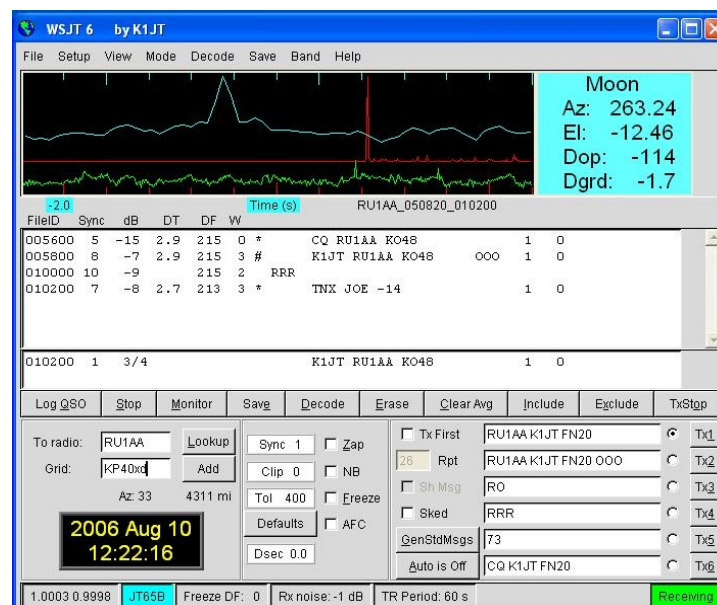
technology breakthroughs in the RF domain. The focus of RF technology development will be on the RF spectrum allocated and needed for space use by the International Telecommunication Union (ITU), where adequate bandwidth would provide a useful service, or where the application is beyond the near-Earth environment.” Specifically: “5.2.2 Power-Efficient Technologies: Flight and ground techniques and technologies that make more efficient use of the available system power”

TA 5.5 Integrated Technologies: “Realizing that there may be advantages to integrating technologies developed across the communications and navigation areas, Integrated Technologies deals with crosscutting technologies that work in combination with the other areas to maximize the efficiency of missions. This focus area also includes the integration of communications and navigation technology developed in other technology areas, such as computing technology and advanced sensors.” Specifically: “5.5.1 Radio Systems: Exploit technology advances in RF communications, PNT, cognition, and space internetworking to develop advanced, integrated space and ground systems that increase performance and efficiency while reducing cost. For example, a multipurpose, software-defined radio might be developed that can change its function with mission phase and requirements or autonomously sense and adapt to its RF environment to improve communications.”

3. Research Plan

The scope of this work is develop a deep space communication system that will not need the DSN. We will develop a portable transceiver and antenna system that can be used with the JT-65 communication protocol for Earth-Moon-Earth (EME or Moon Bounce), modify the software to interface with CubedOS, and test the complete system. To accomplish the project successfully, the work plan will be divided into sub-objectives as follows:

Objective 1: Take the current JT-65 software [12], designed for two human operators, and modify it to be controlled autonomously by our CubedOS software.



The current JT-65 software runs on a Windows or Linux laptop or desktop computer

with a nice user graphical interface. We will modify the interface, so that one copy can be autonomously controlled by our CubedOS software. The graphical user interface shown will be removed, and all the software necessary to control JT-65 will be written in SPARK/Ada in a manner to interface with the rest of CubedOS (which is written in SPARK/Ada). JT-65 is a low data rate protocol that produces error free communications at levels on the order of 23 dB below the noise floor. It allows the transmission of 72 bits of data encoded in 384 bits of including error correcting code. It is optimized for ham radio communication, with encoded call sign recognition, etc., which we will replace with encoded space related items. Dr. Brandon has experience using JT-65 for Earthbound communication, all over the globe with 10W and a 1m pole antenna on the 20m and 40m bands, and with Moon bounce on 70cm. With 4 2m yagi antennas for the 70cm band, or a 1m dish for x-band (8 GHz) one can communicate via Moon bounce, where the path loss is about 262 dB for either band. For a straight line path loss of the same 262 dB, the distance is that of from Earth to Jupiter (4.25 AU, 6.3×10^{11} m). Normally, communication over this distance requires the 70m dish of the DSN. A deep space CubeSat would probably use the DSN for downloading larger quantities of scientific data using conventional protocols, and also using JT-65 would allow for almost continuous communication for spacecraft health monitoring, navigation, flight path control and specialized control of satellite subsystems.

Objective 2: Rewrite the critical portions of JT-65 in SPARK/Ada to greatly reduce possible software errors.

Our experience with SPARK/Ada in our Vermont Lunar CubeSat showed the importance for high integrity software, which was written primarily in SPARK 2005. Some of the software metrics are: 5991 lines of code; 4095 lines of comments (2843 are SPARK annotations). A total of 10,086 lines (not including blank lines). The Examiner generated 4542 verification conditions, all but 102 were proved automatically (98%). We attempted to prove the program free of runtime errors, which allowed us to suppress all checks. The C portion consisted of 2239 lines (including blank lines). Additional provers in SPARK 2014 would allow 100% automatic proofs.

Of the 12 university CubeSats we were launched with, 8 were never heard from, 2 were partially contacted for about a day, and one other worked for 4 months. Ours worked the full two years and two days until re-entry. Studies by the UK Ministry of Defense [13] and NSA [14] show that SPARK/Ada has about 1/240 of the error rate of the C language, and can be written in 1/3 the time (a productivity of 38 lines of code per programmer day from project start to finish (our rate was almost identical) as compared with 10 - 12 lines of code per programmer day with the C language). We will rewrite as much of the JT-65 software as possible in SPARK/Ada, starting with the most critical sections.

SPARK 2014 - Toolset The current version of the SPARK toolset and language definition is SPARK 2014. It is a major enhancement over the earlier SPARK 2005 toolset and language definition we used in our Vermont Lunar CubeSat software. The SPARK 2014 language supports a much larger subset of Ada, allowing more natural designs. The SPARK 2014 toolset uses more modern theorem provers, and is more easily extensible to use additional provers as they become available. All current and future software development done by the CubeSat Laboratory at Vermont Technical College, including the work on Lunar IceCube, is being done using SPARK 2014. The SPARK tools consist of a modified Ada compiler together with a verification condition generator and one or more back-end theorem provers. An additional tool, GNATprove,

performs detailed data and information flow analysis, described in the next section, and generates verification conditions for the provers. Conceptually GNATprove produces a verification condition, or “check,” for every place where the Ada language mandates a runtime check. If these verification conditions are proved, or “discharged,” it means the runtime check will never fail. Examples of such runtime checks include: out of bounds array access, arithmetic overflow, division by zero, and some other things. Furthermore Ada 2012 allows the programmer to include pre- and post-conditions on subprograms, as well as other assertions, that encode higher level correctness properties (e.g., a sort procedure produces a sorted permutation of its input). Again, GNATprove generates verification conditions that, if discharged, will statically show those properties will always hold.

The GPS integrated development environment developed by Adacore provides a convenient front-end to the SPARK tools. Using the tools can be as easy as selecting “Prove File” from the GPS menus. The result is a list of locations where unproved verification conditions exist, if any. The programmer can then view and edit those locations as necessary.

Proofs fail for three reasons:

- The code is incorrect. The check being analyzed might actually fail.
- The theorem prover(s) are not powerful enough to complete the proofs.
- There is insufficient information in the program to complete the proofs.

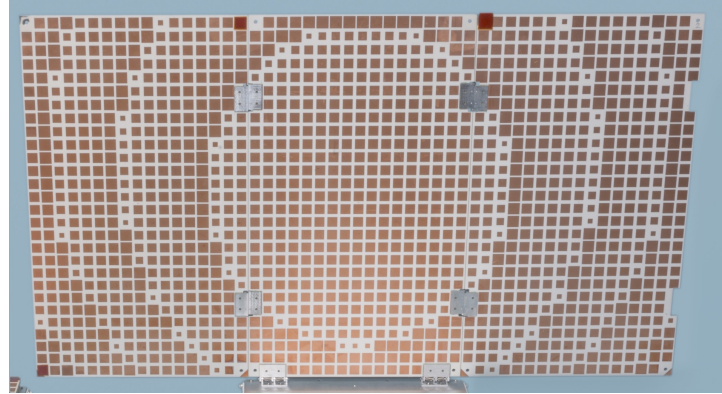
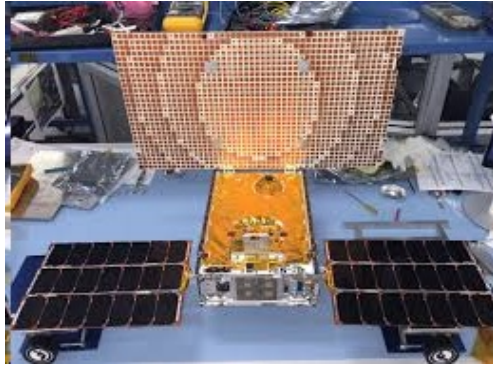
Most of the skill in using the SPARK tools is in determining which of these cases is the problem, and in modifying the program to deal with that situation. It is important to understand that the GNAT Ada compiler can insert runtime checks for all the SPARK assertions as well as the Ada language mandated checks. Once all checks are proved, the runtime checking can be disabled, saving both space and time in the final program without compromising safety.

Objective 3. Test the software with a portable ground station and the Vermont Tech CubeSat Lab ground station using Moon bounce.

We will put together a portable ground station consisting of an Icom IC-9100 [15]



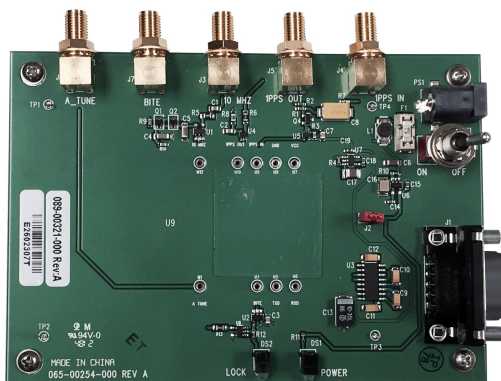
which is specifically designed for satellite communication. We have its predecessor, the IC-910H in our CubeSat Lab, and we will set up JT-65 Moon bounce communication between the two stations. We have both 70cm and 2m steerable crossed yagi antennas at the CubeSat Lab ground station on a 50 foot tower. We will purchase a 70cm crossed yagi designed for Moon bounce [16], for the portable station. During operation, we will collect data on all of our contacts including the retransmission rate, effective data rate, signal strength, EME distance. We hope to show the viability of JT-65 for deep space satellite communication. Although we will be testing with 70cm radios (X-band and higher are much more expensive), with the appropriate antennas, it could also be used for higher frequencies. For example, the X-band MarCO CubeSats.



The MarCO, a 6U CubeSat (10 cm x 20 cm x 34 cm, 7.8 kg) with a 60 cm x 34 cm reflectarray antenna shown to the right.

The two MarCO CubeSats [17], which accompanied the InSight Mars lander [18] had a high gain (29 dB) reflectarray antenna [19] which should work for communication from Jupiter to Earth. It was used for high data rate communication with the 70 m dish of the DSN, but such a spacecraft could communicate small pieces of data much more frequently with JT-65 and a typical university 3 m dish ground station.

Timing is important in using JT-6. When away from the Earth, the precise timing from the GPS constellation is not available. We will be using the Microsemi SA.45s Chip-Scale Atomic Clock.



Development Board



Clock Chip

This cesium atomic clock in a 4.0 cm x 3.5 cm x 1.1 cm package is accurate to about 10 ms per year.

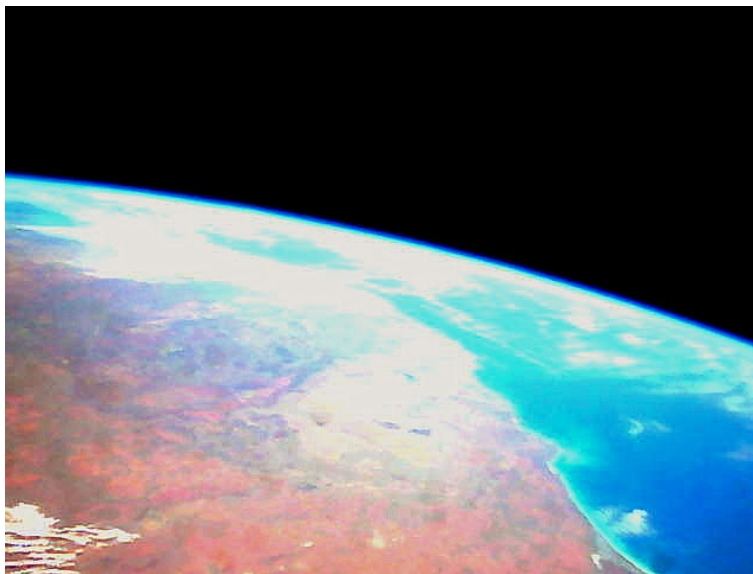
Alignment with NASA Research Priorities

In 2015, NASA and National Research Council (NRC) jointly published “NASA Space Technology Roadmaps and Priorities” [11], recommending the overall technology investment strategy and prioritization of NASA’s space technology activities. Among fourteen identified technology areas, following two aspects of Technology Area 5: Communications, Navigation, and Orbital Debris Tracking and Characterization Systems. In TA05 roadmap the fundamental technology focuses related to our proposed research are listed as below:

TA 5.2: Radio Frequency Communications: “Radio Frequency (RF) Communications strives to dramatically accelerate techniques in use today for NASA’s missions. RF technology development concentrates on getting more productivity out of the constrained spectrum bands that are allocated to space users. Although it is quite a bit more mature than optical communications, there is still a great deal of promise for technology breakthroughs in the RF domain. The focus of RF technology development will be on the RF spectrum allocated and needed for space use by the International Telecommunication Union (ITU), where adequate bandwidth would provide a useful service, or where the application is beyond the near-Earth environment.” Specifically: “5.2.2 Power-Efficient Technologies: Flight and ground techniques and technologies that make more efficient use of the available system power”

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The deep space communication system we will be developing and characterizing is well aligned with the areas listed above. Last summer, Dr. Brandon and Dr. Chapin spent a week at JPL discussing this and other aspects of our CubedOS with a number of NASA researchers, including Dr. Richard Hodges, the developer of the MarCO reflectarray antenna. Dr. Jay Goguen, was our host for the entire week.



First photo returned by Vermont Lunar CubeSat, North coast of West Australia.

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Testing a more fade resistant BPSK demodulator for Fox Linear Transponder spacecraft

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Keywords: BPSK Demodulation, DBPSK, FoxTelem, Costas Loop, Coherent vs Non-coherent decoders, Dot Product Detector, Java

Abstract. At the 2018 Symposium I discussed a Costas Loop implementation that would avoid false lock and demodulate BPSK in software. Phil Karn, KA9Q, suggested this may not be the best solution for a small spacecraft with deep fades. The fades would break the lock. This paper discusses the design and testing of a non-coherent Dot Product based demodulator which should be more resistant to deep nulls and fades.

Part 1: Dot Product BPSK Decoder

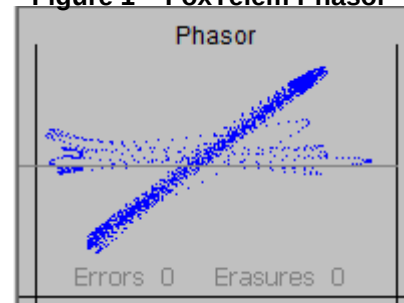
Based on the work of Phil Karn, KA9Q[1], I have implemented a new non-coherent Dot Product based BPSK Decoder for FoxTelem. A Dot Product decoder should perform better than a coherent Costas Loop decoder, which is vulnerable to fading and loses track of the carrier. This paper discusses the implementation and tests how the Dot Product decoder performs compared to the Costas loop decoder.

Step 1 was understanding how a non-coherent Dot Product BPSK decoder works and then how it should be implemented in FoxTelem.

Dot Product Phase Change Detector

A dot product is the product of two vectors. In this case we are examining the phase vector of the BPSK signal. In the phasor diagram in Figure 1 you see the phase vector plotted for many bits. This is a straight line because it is showing two phases that are 180 degrees apart, which sounds right for BPSK. In this case you can imagine two phase vectors, one pointing at about 45 degrees and another pointing at about 225 degrees. Ignore the horizontal "noise". Note that this is a line rather than two dots because the amplitude is changing for each bit. This may well be an issue that needs to be addressed in the decoder.

Figure 1 – FoxTelem Phasor



Our signal is differentially encoded, making it DBPSK, and meaning that the absolute phase does not matter. We don't need it to oscillate between 0 and 180.

Instead if the phase changes from one bit to the next then we have a "0", if the phase stays the same then we have a "1".

If we take the dot product of the phase from one bit and multiply it by the phase from the next bit, then we have a clear indication if the phase has changed. If the phase is the same, then the dot product of two identical vectors is a vector with twice the length. If the phase is the opposite, then the dot product should be zero. This is much less sensitive to phase inaccuracies than the Costas loop, which must be locked to 0 and 180 degrees.

Frequency and Clock Recovery

The Dot Product decoder still needs to be on the right frequency, even though it can tolerate some phase shift. It also needs to align with the data to sample it correctly. That means we need to recover the carrier and the clock.

The dot product calculation is very fast because it is not a convolution. Phil Karn's algorithm simply runs the calculation many times at different offsets and uses the maximum magnitude (energy) to determine when we are aligned to the right frequency and at the right phase offset.

You can see the details in the FoxTelem Java code[2] or look at Phil Karn's original reference implementation in C[1]. Phil's algorithm is summarized below:

1. Ingest a buffer of audio data that holds a set of symbols (100 in my implementation) at 48000 samples per second, or 40 samples per symbol for our 1200bps BPSK
2. Run a Dot product demodulation on every bit at every sample offset and across a range of frequencies. Use this to determine the carrier frequency to +/-100Hz and the phase offset. Repeat this every few seconds but not every buffer
3. Run two dot product demodulations above and below the estimated carrier, one at +75Hz and one at -75Hz. Then calculate the dot product of the symbols to approximately determine the bit sign and use it together with the cross product to work out if the frequency is positive or negative. Meaning our estimate was too high or too low. From the two results we estimate the carrier by linear interpolation
4. Finally, run the actual demodulation at the estimated carrier frequency and at a set of sample offset from early to late. Each sample offset is a phase offset. We use the magnitude to determine which offset was best and take those bits as the results. Use the calculated offset to adjust the phase for the next buffer. Phil Karn used three offsets, I use a larger set, determined experimentally.

Part 2: Simulating Doppler and Fading

With the non-coherent Dot Product demodulator implemented the next question is how to test it? I could use a spacecraft in orbit and record some telemetry from it, but we do not have a spacecraft in orbit with the PSK format that I am decoding. I can generate the signal in the lab, but it does not have Doppler or fading. I decided to write a program called SimSatellite[3] that would layer the Doppler shift and fade on top of an existing signal.

The Design

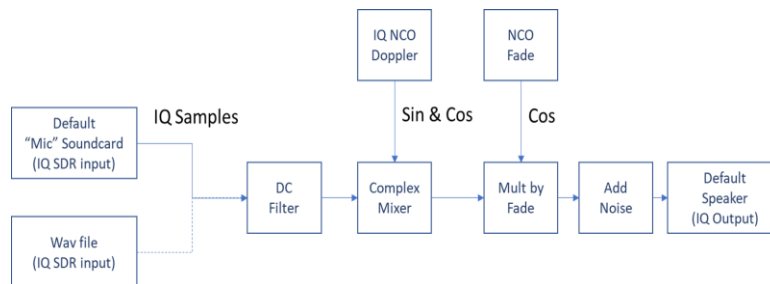


Figure 2 – Block Diagram of SimSatellite utility

The program flow is shown in Figure 2. First it reads from either the default soundcard, or from a wave file. The IQ audio is read from the source and DC filtered. This removes the central DC spike from the SDR. Without this the central spike will travel with our Doppler shift. Which is not what we want!

Then the program mixes the IQ samples with the Doppler offset frequency. For example, if the spacecraft is nominally on 435.750MHz and the Doppler offset is 10kHz, then it mixes the signal with 10kHz. But this is not a mix in the traditional sense, which would create a sum and difference frequency. We mix with a complex oscillator and it cleanly shifts the signal according to the Doppler with no artifacts and no image.

Next we multiply the signal by a fade amount. If we simply scale the signal by an amount it has no effect, because the noise and signal vary by the same factor. Instead we add a fixed amount of noise to keep the noise floor constant and then vary the signal level. Then the signal will sink into the noise as we apply the fade. Which is just what we want.

The educated reader will want to know what type of noise. In this case average white gaussian noise is a good model to use, though in practice it did not seem to make a difference vs random noise.

What type of Fade do we apply?

With a bit of thought I realized the antenna pattern is rotating and that the fade is not sinusoidal. I fired up EZNEC and modeled a quarter wave antenna in free space

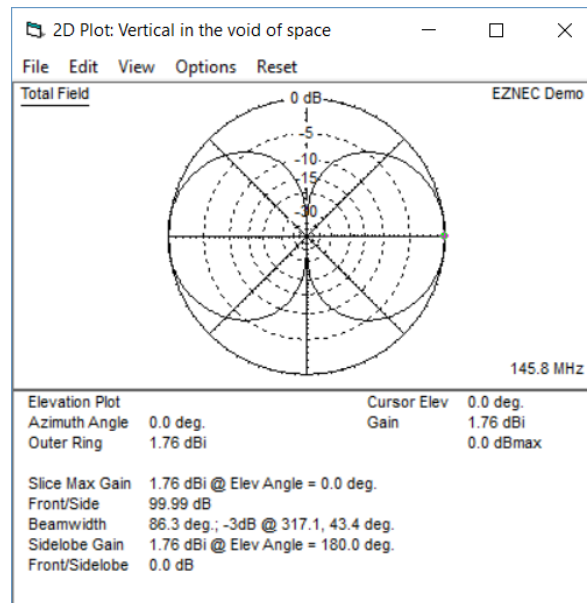


Figure 3 – EZNEC plot of a quarter wave antenna pattern

The pattern in Figure 3 has a strong response for most of the rotation with two deep nulls. Easy NEC allowed me to export the data from the plot and I loaded the values into my program. We now have the antenna pattern as a fade response. We can specify any period we want.

Applying the Doppler shift

I thought a simple constant change in frequency would be enough to test the Doppler. Perhaps I could model the maximum change per second and see if the decoders could hang on. That worked to an extent, but it was difficult and artificial. So instead I used the Java port of the Predict library[4] by David Johnson, G4DPZ. It did not have the Doppler calculations that I needed, so I added them [5].

SimSattelite

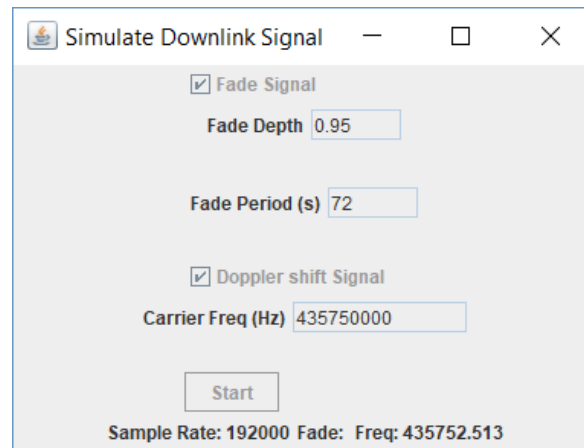


Figure 4 – SimSatellite setup for 72 second rotation

The program runs well and produces a signal shifted according to the Keplerian Elements being used. Fading is applied according to the parameters specified.

Part 3: Testing Coherent vs Non Coherent

Before we get into the tests, we should remember that in an ideal situation a coherent demodulator like the Costas Loop performs better than a non-coherent decoder like the Dot Product demodulator. Theory tells us that with a long steady signal a Costas loop will decode more frames. That is proved easily with testing in the lab. The Costas loop can decode about 2-3dB further into the noise than the Dot Product decoder.

We are therefore interested in what happens with a realistic signal that is shifting with Doppler and fading as expected. Then which decoder will be better?

Test 1: 5dps, Deep Fade, Antenna Pattern Rotating

We want to simulate the rotation of the antenna pattern. Our CubeSats are partially stabilized with a magnet which keeps them aligned to the earth's magnetic field. This is designed to keep the 2 meter and 70 cm quarter wave antennae in a somewhat "vertical" position. Or at least vertical with respect to the Z axis. They are then rotating around Z because of sunlight pushing against the solar panels. The panels are slightly offset so that the force is uneven, and the spacecraft rotates slowly in one direction. In theory the null is in line with the antenna and points towards the ground, in practice it will sweep across the ground with a similar period to the rotation of the spacecraft.

For testing we will use a simplifying assumption that the antenna pattern rotates with a similar period to the spacecraft, even though the actual antenna movement is much more complex.

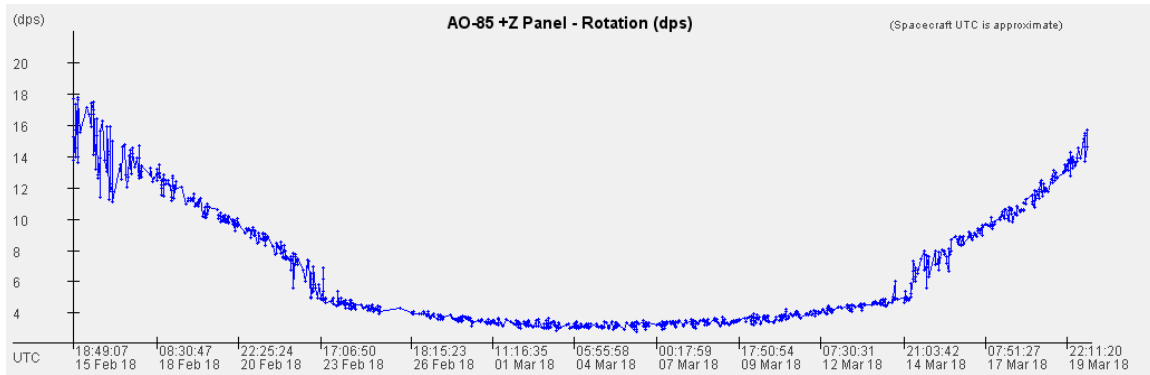


Figure 5 – AO-85 rotation as an example for comparison

I took a quick look at AO-85's rotation around Z as shown in Figure 5. It is hard to pick a typical rotation rate, but it might frequently be as much as 5 degrees per second (dps) or one revolution in 72 seconds. Clearly sometimes it is higher. I used the Doppler and Fade Simulation program described in Part 2 to simulate that fading. For Doppler shift I modelled the orbit of AO-92. The receiver was a Funcube Dongle listening to a flat sat transmitter with a realistic signal level, but well above the noise.

The fade model applied was a quarter wave whip antenna pattern with a 95% fade out, meaning it will disappear all the way into the noise about twice a minute. I ran this for 10 minutes, repeating the test several times. In Figure 6 you can see the dot product decoder on the right, with a rotating phasor, but always a straight line. Costas is on the left with the classic two dots in the phasor that we see in the text books, because the phase is locked.

The Dot Product decoder has 103 frames vs 87 frames for Costas. It is nearly 20% better. This looks very promising.

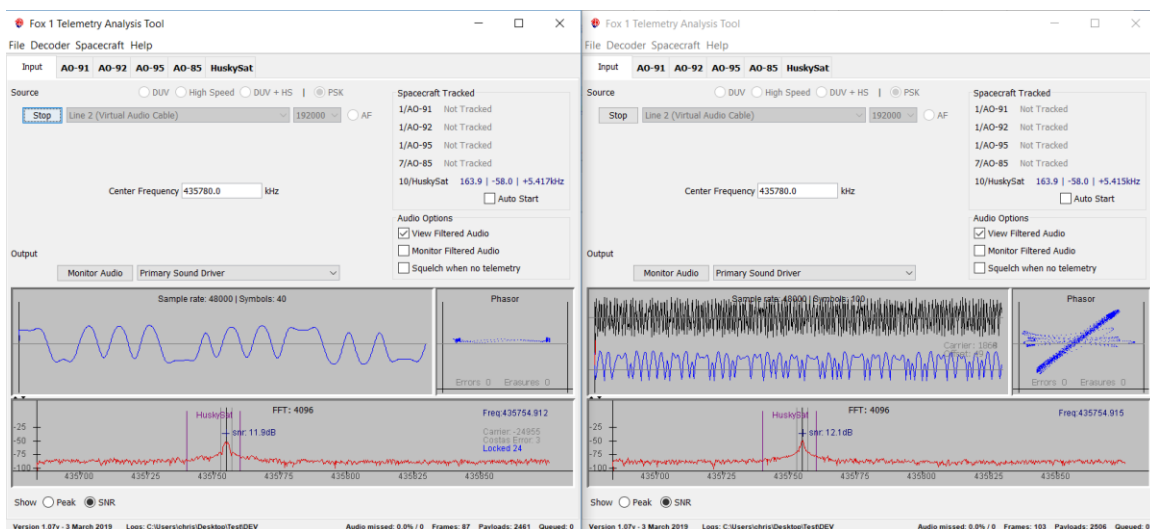


Figure 6 – Costas and Dot Product Decoders after Test 1

Test 2: 20dps, Antenna Pattern Rotating

I took a bit more time and examined the rotation rate for AO-92. People with more knowledge than me suggested it as a suitable model for the future orbit of Fox-1E. I also know that AO-92 has given us some difficulty talking pictures with its camera [6] due to its fast rotation. The spin is typically much faster than 5dps. Figure 7 shows the rotation rates during 2018 and they span from -20dps to +20dps.

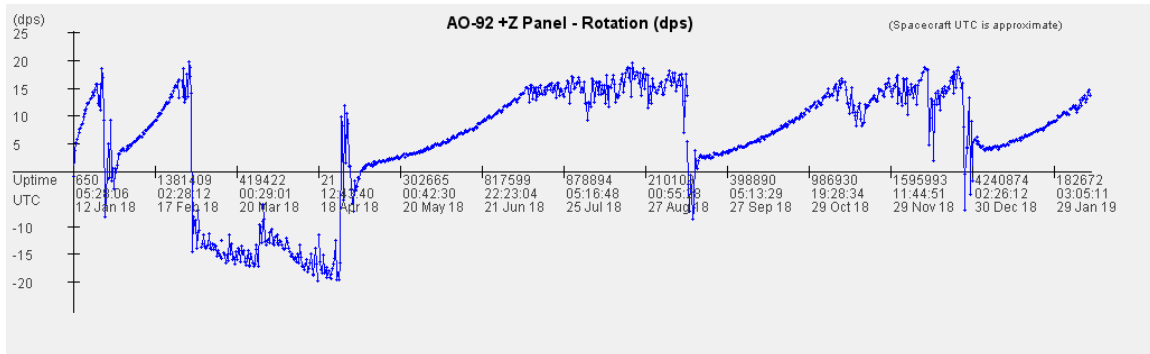


Figure 7 – AO-92 Rotation rate analysis

Perhaps a realistic rate is 15dps, which is 24 seconds for a rotation. This was modeled in SimSatellite. Two copies of FoxTelem were again run in parallel, the flat sat transmitter was started, and the results are shown in Figure 8. Now the Dot Product Decoder gets twice as many decodes. This feels like an important result because the fast rotation has given us difficulty with FSK. But it is not the end of the story.

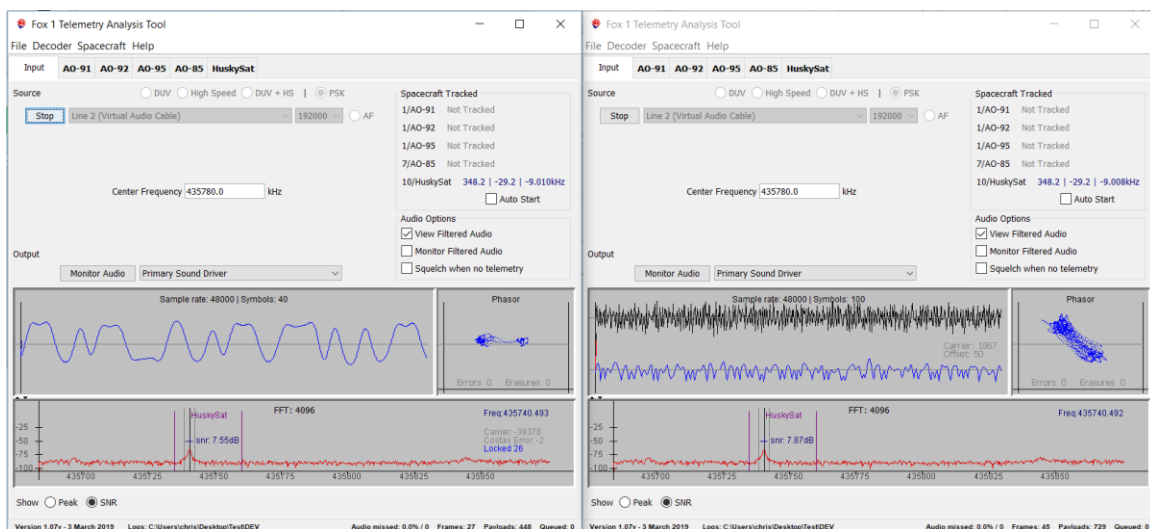


Figure 8 – Costas and Dot Product Decoders after Test 2

Test 3: 5dps, Polarization Changing

The spacecraft is supposed to rotate around Z so that we have a nearly vertical antennae as it passes across the sky. Even if that were true, the antennae polarization (angle) changes with respect to the ground station as it passes overhead. Some stations use a Circularly Polarized antenna at the ground station to mitigate this effect, but many do not. This test models a linear antenna at each end of the telemetry link.

The polarization mismatches do not have the sharp nulls that we see in the antenna pattern. Instead the Polarization Loss Factor (PLF) for two linearly polarized antenna at an angle theta is the square of cos theta. Cos squared is very similar to a raised cosine and is shown in Figure 9. Note that it is at twice the frequency.

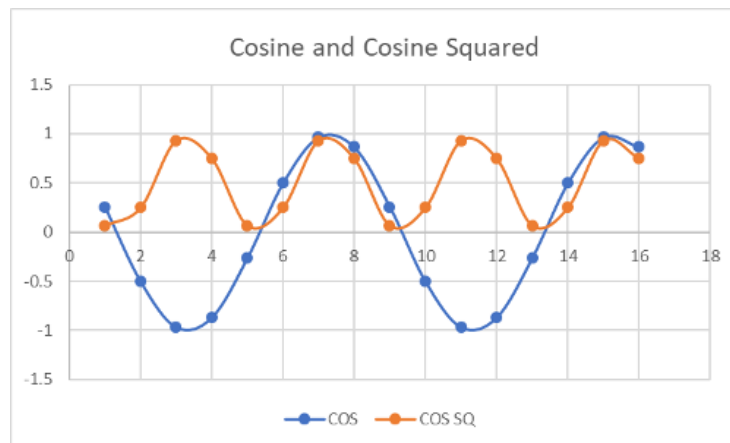


Figure 9 – Polarization Loss Factor (PLF) for two linearly polarized antennae (in orange)

In test 3 I modeled the fade with a cosine squared pattern to simulate the mismatch to a linear antenna with the cycle repeating every 72 seconds to simulate 5dps. The results are shown in Figure 10. Now the Costas Loop is much better.

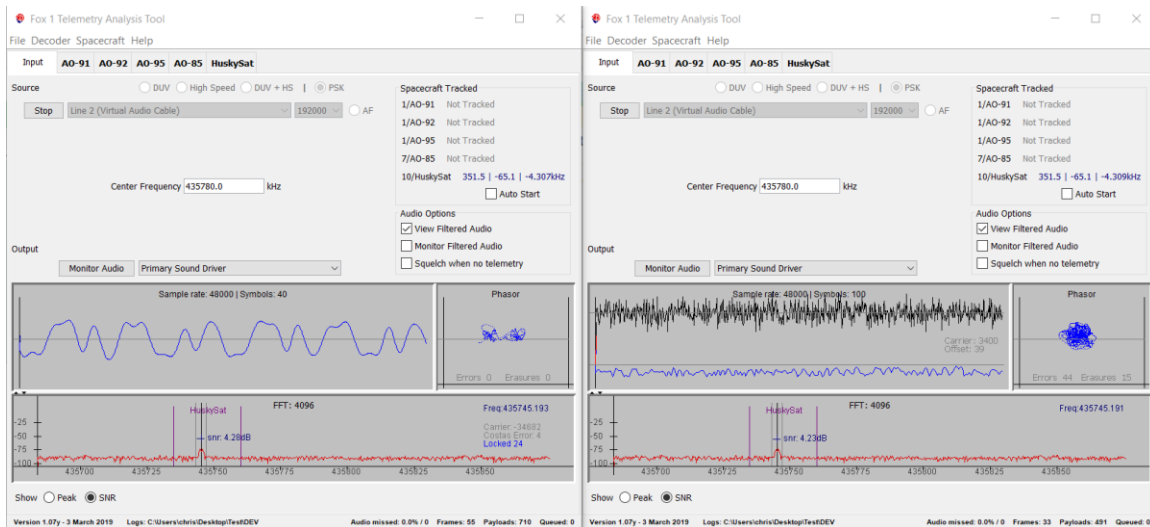


Figure 10 – Costas and Dot Product Decoders after Test 3

I repeated this test with several combinations. If the signal is stronger, or the fade is not as deep, then the gap narrows but Costas is always at least 5% better. If the fade is more rapid, say 30dps, then Costas is 30% better. There seems to be no combination with this fade pattern where the Dot Product decoder is better.

Conclusions

If the signals are strong and there is no fading then both decoders perform well, with the coherent Costas decoder having a slight edge. The Costas Loop is less susceptible to noise and is better with weak signals. It can decode a signal 2-3dB above the noise. The current version of the Dot Product decoder needs a signal 4-5dB above the noise.

For a rotating quarter wave antenna pattern, where the signal fades into the noise during the null, the non-coherent Dot Product decoder outperforms a Costas Loop. In a realistic test it can be 30% better. This assumes the ground station is using Circular Polarization and it not suffering long slow fades due to polarization mismatch.

If the ground station is using a linearly polarized antenna and the fading has a cosine squared shape, then a Costas Loop, with its better low signal handling, outperforms the current Dot Product decoder. Sometimes as much as 30%.

A combination of antenna nulls layered on top of polarization mismatches will favor one decoder or the other, depending on which fade is more pronounced.

The final recommendation might therefore be "run both decoders" and why not if you have enough compute power. It will be interesting to see what happens with real signals.

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CatSat: Pathfinder for New Ham Satellite Opportunities

Michael Parker (KT7D), Rincon Research Corp.; Christopher Walker (K7CKW), Univ. of Arizona/FreeFall Aerospace Inc.; Douglas Stetson, FreeFall Aerospace Inc.

1. Opportunities

Recently two interesting opportunities arose for amateur radio through cooperation with the University of Arizona (UofA) and two local Tucson companies, FreeFall Aerospace Inc. and Rincon Research Corporation.

a. Antennas

The first opportunity (described here only briefly) involves six, 6.1 meter diameter radio telescopes recently acquired by the UofA's Steward Observatory with support from Rincon Research Corp. Until recently the antennas were part of the Berkeley Illinois Maryland Array (BIMA) for millimeter radio astronomy and used at frequencies as high as ~250 GHz. Figure 1 shows the antennas before shipment from Owens Valley, CA. Five of the antennas are now located in the Tucson area. The sixth is located at the Rincon Research facility in Centennial, Colorado. Both organizations are interested in public outreach. This means that significant time will likely be available for amateur radio activities on at least two of the antennas.

These antennas are particularly sensitive and suited for operation above 10 GHz. Current thinking is that the antennas will be configured to support 10.5 GHz Moon bounce, as well as to serve as ground stations for the CatSat satellite described below. Some, perhaps all, of the antennas will have cooled, low-noise, mmWave receivers suited for radio astronomy.

Suggestions about use of these antennas for experiments, cis-lunar communications, etc. are invited. The first of these antennas is expected to be assembled by the end of 2019, followed quickly by two more.



Figure 1. Arizona Array Antennas. Each antenna is a fully steerable, 6.1 meter parabolic reflector that can operate up to ~300 GHz.

b. Satellite

The second opportunity involves the launch of a 6U CubeSat, targeted for late 2020. The project named CatSat, after the UofA mascot, began in 2018 as a student-faculty design study in cooperation with FreeFall Inc. The objectives of CatSat are twofold; 1) to serve as a technology demonstrator of a high bandwidth communications link from a smallsat and 2) to study high frequency (HF) propagation between the Earth's surface and low Earth orbit (LEO). To achieve a high bandwidth telecom link with the limited transmitter power available on a CubeSat, CatSat will utilize a new, deployable antenna invented at the UofA and being further developed by FreeFall Inc. The antenna consists of an inflated Mylar sphere, where one hemisphere is

metallized and the other remains clear. The metallized hemisphere serves as a spherical reflector that focuses the incoming radio waves passing through the clear side of the sphere to a focal line located $\sim 1/4$ of the sphere's radius in front of the metallized surface. A linefeed located at the focus collects the radiation coming from different parts of the reflector and delivers it to a radio via transmission line. A 3D CAD rendering of CatSat is shown in Figure 2. The Arecibo Radio Observatory utilizes a very similar approach. There a linefeed collects radiation from a ~ 1000 ft spherical reflector. The Arecibo reflector is too large to physically move. However, the wide field of view of the spherical reflector allows the telescope to be pointed by moving the linefeed. For CatSat a new, phased array linefeed (PAL) was invented that allows the reflector's beam to be steered $\pm 15^\circ$ electronically, thereby obviating the need to precisely control the orientation of the spacecraft to maintain lock on a ground station. The inflatable antenna for CatSat is being developed and donated by FreeFall Inc. An early version of the antenna that was tested from a NASA stratospheric balloon is shown in Figure 3. As a demonstration of the power of such an antenna system, CatSat will downlink high definition images from space to the ground. For probing the Earth's ionosphere CatSat will also carry

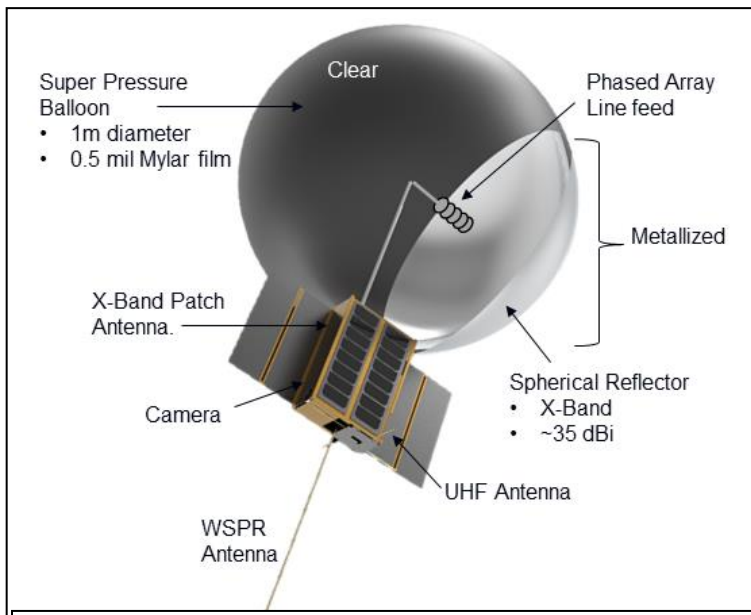


Figure 2. CatSat Schematic. CatSat is a 6U CubeSat that will demonstrate a high bandwidth X-band telecom link using an inflatable spherical reflector. It will also probe the Earth's ionosphere by simultaneously monitoring WSPR signals from Earth from 5 to 30 MHz.



Figure 3. Stratospheric TestFlight. The technology behind CatSat's inflatable spherical reflector was tested 30 miles up on a NASA high altitude balloon flight in August 2018.

a broadband receiving system that will be able to receive 1000's of WSPR beacons or FT8 signals worldwide. The detections will provide a unique dataset that can be used to constrain models of the Earth's ionosphere and the effects of space weather.

By late 2018 several key design decisions had been made. Based on an inflated antenna diameter of about a meter and an operating frequency of ~ 10 GHz, a 3 dB beam width of $\sim 2^\circ$ is expected. This requires pointing accuracy of about 1° . In order to observe antenna inflation, a still camera and low-gain downlink will be included. To add functional redundancy and demonstrate the benefits of a high-gain, inflatable antenna, CatSat will also have the ability to switch its microwave downlink signal between a low-gain patch antenna and the high gain, inflatable antenna. A UHF up/downlink will be used for command and control of the satellite. In November 2018 a proposal to fly CatSat as part of NASA's CubeSat Launch Initiative program was submitted and approved. CatSat is now a candidate for a piggy-back launch opportunity to a ~ 500 km, sun-synchronous orbit in December 2020.



Figure 4. AstroSDR from Rincon Research Corporation. The board contains a software-defined radio (SDR), FPGA signal processor, ARM processor, and data storage.

2. Time Passes

In late 2018 Rincon Research heard about the satellite project and offered to donate an AstroSDR, a powerful, single board CubeSat radio. The AstroSDR is similar to the satellite radio planned for the original Phase 4B ride share, see Figure 4. This board has now flown in space several times. Its high-performance FPGA must be programmed to fully utilize the unit's performance. However, the FPGA solves some problems and offers unique opportunities.

In order to meet the challenge of a December 2020 launch, the CatSat team is currently exploring the possibility of purchasing a 6U spacecraft bus. Several smallsat vendors can provide a 6U bus that meets mission requirements, thereby allowing the CatSat team to focus its efforts on developing the X-band and WSPR experimental payloads.

3. X-Band System

Since the AstroSDR can output any frequency up to 6 GHz, a 10.5 GHz transmitter can be implemented by using its output as a 1st IF frequency followed by up-conversion utilizing an oscillator driving a mixer with one or more amplifier stages. For example, an AstroSDR output at 3.5 GHz might be mixed with a 7 GHz local oscillator and the sum frequency of 10.5 GHz selected for power amplification. A block diagram of the satellite electronics as of early Sept 2019 is shown in Figure 5. A computer-controlled switch provides the capability of routing the X-band output to either a low-gain antenna or the high-gain inflatable antenna. The low-gain antenna will be the primary communication path to most ham stations since the narrow beam of the inflatable antenna will only illuminate one city at a time.

Also note that the diagram shows a 10.5 GHz receive capability in addition to transmit. Exactly how this would be used, if implemented, is open for discussion. With the addition of the AstroSDR, the possibility of implementing a linear transponder 5.9 GHz up and 10.5 GHz down

can be considered. This would be straightforward to implement using a 5.9 GHz LNA feeding the AstroSDR. However, several factors should be considered. First, the narrow beamwidth of the 10.5 GHz high gain antenna in LEO would only cover one city at a time. To maximize spatial coverage the low-gain spacecraft antenna would be used. This would in turn require precise pointing of a ham's narrow-beam ground antennas at the LEO to close the link. Second, Doppler compensation would be quite a project for the ground stations, since the frequency shift would be more than plus-minus 300 kHz. Third, the life-time of the satellite is projected to be ~1 year due to atmospheric drag. Given all the above we believe that few hams would want to make the necessary investment of time and effort to utilize the transponder.

Finally, discussions with individuals who continued working on digital ground stations similar to the five and dime concepts associated with the defunct phase 4B ride share revealed there is a desire for a system capable of on-board multiple access channelization of the uplink and onboard processing resulting in a single DBV-S2x downlink. This appears too complicated for CatSat to handle in the short time available before launch. Instead, the CatSat team proposes transmitting a DVB-S2x signal at 10.5 GHz for test and calibration purposes. At a minimum CatSat could plan to transmit some stored DVB-S2x test patterns and, probably, also transmit still and/or video from on-board cameras.

4. HF Ionospheric Experiment

Due to orbital motion, the transmitted signal from a WSPR transmitter on CatSat will be Doppler shifted. There could also be dispersive and refractive effects due to the ever-changing structure of the ionosphere. Therefore, reception of a WSPR transmission from CatSat would require the receiving software to be modified to compensate for these effects. An alternative approach would be to receive WSPR signals on orbit and relay them to ground using the 10.5 GHz downlink. Utilizing the wide bandwidth of the AstroSDR, it then becomes possible to receive *all* WSPR signals occurring in multiple HF bands. For example, a 125 MHz local oscillator can be used to up convert the entire HF band from 5 - 30 MHz to 130 - 155 MHz. An AstroSDR tuned to 142.5 MHz would then have the entire HF band in its digitized passband. The FPGA programming in the AstroSDR can then select multiple narrowband segments, say 2.5 kHz wide containing signals of interest. For example, one might tune to WSPR activity on 20 meters with one 2.5 kHz passband while simultaneously listening to FT8 on 30, 20, and 10 meters. After all, "it's just software". The 4 digital receivers could then be combined into a 4-channel frequency division multiplex signal with a total bandwidth of 10 kHz for transmission to ground over 10.5 GHz. The basic concept is diagrammed in Figure 6. Alternatively, the 4 channels which are already digital could be combined into a time-division multiplex signal and digitally modulated onto the downlink and received at 10.5 GHz. The ground station could record the entire 10 kHz bandwidth and play it back, de-Doppler processing and demodulating one station at a time. Depending upon band conditions, each 10.5 GHz receiving station could copy dozens of HF ham stations on each satellite pass. Since the stations broadcast their location, propagation conditions from many locations to the satellite could be determined on many simultaneous frequencies. Serious experimenters spaced around the world could share recorded data to form a picture of propagation over the entire orbit of the satellite.

An alternative plan would be to store the 10 kHz wide FDM signal, or its TDM equivalent, in the AstroSDR's digital memory. Then, when in view of a high-performance ground station, it could be played back over the low-gain transmit antenna at 10 times the original rate (100 kHz bandwidth). In such a case 10 minutes of transmitting would play back 100 minutes of the

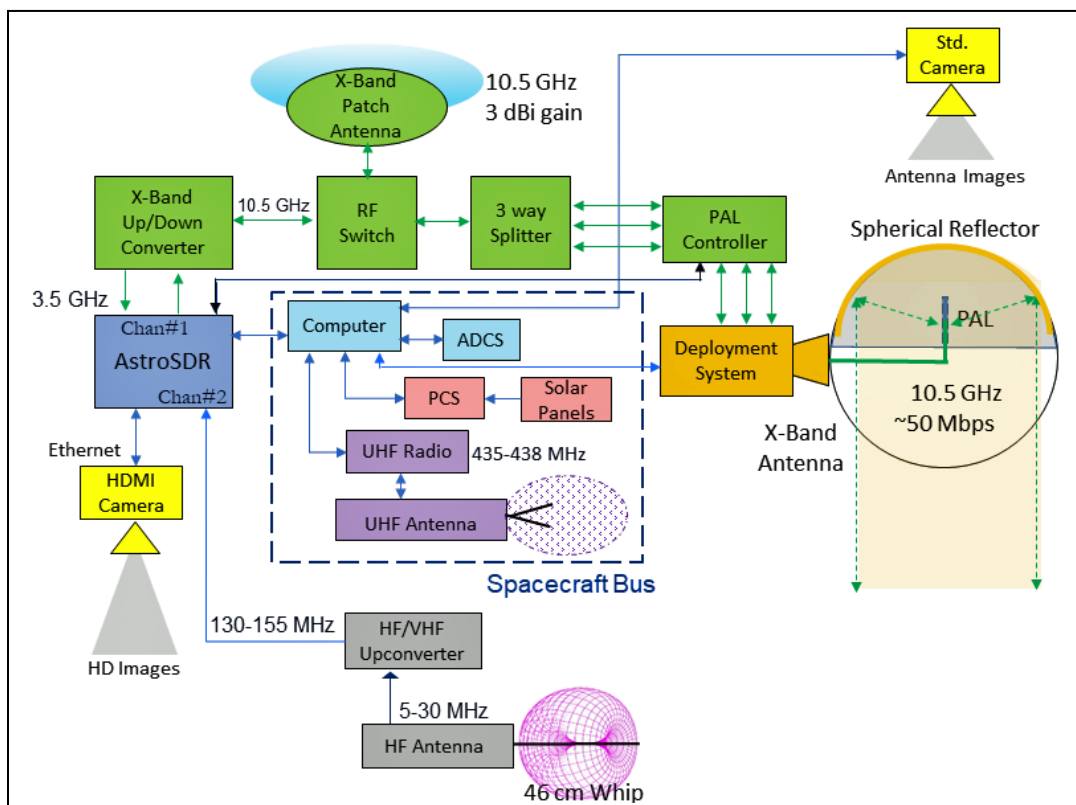
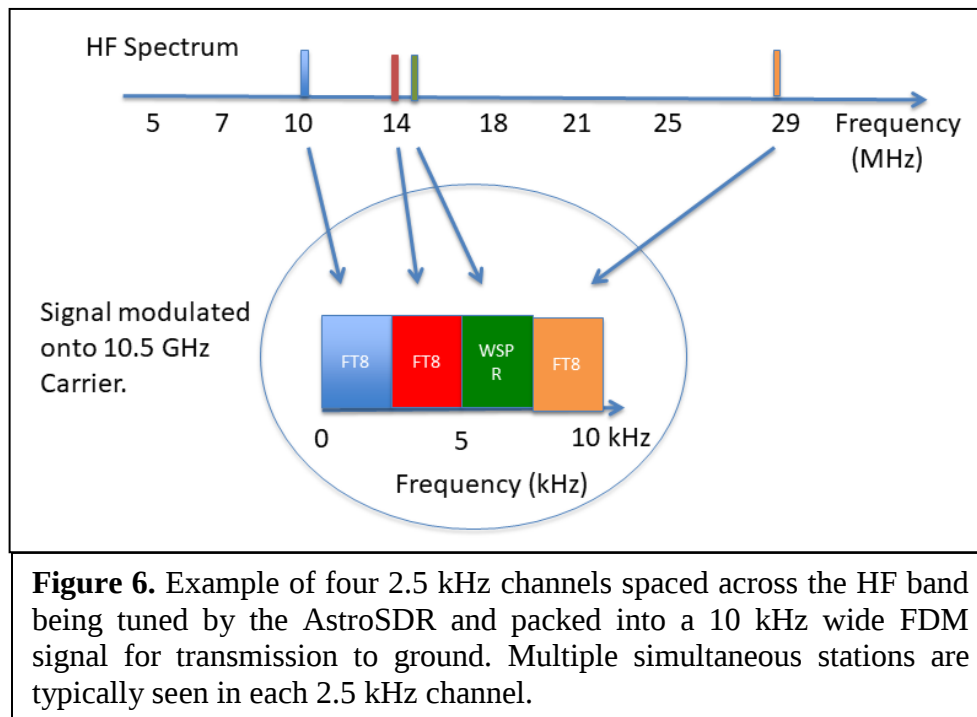


Figure 5. CatSat Block Diagram. CatSat will be the first CubeSat utilizing a deployable, spherical reflector to establish a high bandwidth telecom link to relay high definition images to Earth. It will also utilize a state-of-the-art SDR to receive and relay WSPR signals recorded in orbit to X-band ground stations.

previous pass, an entire orbit around the Earth! With the high gain satellite antenna this data compression approach can be used to great effect. When the high gain satellite antenna is pointed at a high gain ground station, such as the 6.1 meter dish, one might play back at 1,000x (10 MHz bandwidth) the original collection rate. Table 1 shows the performance of some possible combinations of satellite and ground antennas together vs. downlink bandwidth. One watt of X-band RF power was assumed. A 0.6 meter ground station antenna pointed at the satellite omni directional antenna can easily support 10 kHz bandwidth of real-time HF or transmission of a frame-grabbed picture. If the Satellite's Hi-gain antenna were pointed at the 0.6 meter ground station, real-time TV could be supported. A 10 kHz downlink could be established to a non-pointed antenna with hemispherical coverage. Downlink Calculations include 3 dB polarization loss and 3 dB pointing error for each dish antenna. A gain of 35 dB is assumed for the satellite high gain antenna. A goal could be to record 50 kHz of bandwidth, equivalent to 20 simultaneous SSB receivers tuned across the HF ham bands for 24 hours. All the data could then be dumped in one 10 minute pass over Tucson. These data would cover the entire world and could be made available over the internet. So, a ham might log into a server and listen for her or his own signal and other signals as heard by a satellite over the south pole and later in the orbit over the equator. This has the potential of being a powerful research tool. A researcher able to decode the transmitter info could know the location and strength of all signals being heard by the satellite as it orbits the earth. And since multiple ham bands are being covered simultaneously, the info

would be available as a function of frequency. To cover multiple ham bands simultaneously will require a significant FPGA programming effort, but this is now our goal.



5. Summary

CatSat and the Arizona Array offer hams the opportunity to push the frontiers of technology in classic ham fashion. The inflatable antenna experiment and the Arizona Array of dishes are both on the leading edge of technologies that will be developed as spacecraft shrink and more space vehicles fly to greater distances. On the other hand, the HF experiment addresses questions about HF space-to-Earth propagation that have existed since some of us listened to Sputnik I with our ham radio receivers. The existence of a worldwide network of HF ham stations broadcasting their positions, combined with CatSat and the clever use of digital signal processing will likely reveal unexpected phenomena. Given the creativity of hams, we expect CatSat will be just the beginning of another chapter in space exploration enabled by amateur radio.

Table 1. SNR performance of different satellite antenna and ground station combinations at 2,000 km range.

Configuration	SNR		
	10 kHz BW Real-time HF or Frame Grab image	10 MHz BW Real-time TV or 50 KHz HF Sped up 200X to dump 33hr of HF in 10 min pass	500 kHz BW HF 50 kHz Sped up 10x Dump orbit In 10 minutes
Satellite omni to Ground 6.1m dish	39 dB	9 dB	22 dB
Satellite Hi Gain to Ground 6.1m dish	71 dB	41 dB	54 dB
Satellite omni to Ground 0.6m dish	18 dB	-	1 dB
Satellite Hi Gain to Ground 0.6m dish	50 dB	20 dB	33 dB
Satellite Hi gain to Ground 3 dB gain	16 dB	-	-

ⁱPSAT1U - A Low-Cost, Easy-Build 1U CubeSat for Hands-On Lab and Space Applications

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Abstract

The majority of US Naval Academy student amateur satellite projects evolved with a primary communications payload based on AX.25 packet radio. The original 10" cube satellite PCSAT (NO44), launched in 2001 (still semi-operational), used discrete components and chips and hardware TNC's (Terminal Node Controllers). Through eight other missions, the design was condensed down to fit the entire AX.25 comms payload on just half of a single 3.5" square CubeSat card and flew on the successful PSAT (2015) and PSAT2 1.5U CubeSat in June 2019. This paper summarizes the final condensation of this basic comms architecture down from 1.5U to a single 1U CubeSat frame while retaining plenty of mission power for communications users worldwide and to support at least 1/3U of additional payload volume. The PSAT1U design is so low cost that it is possible for undergraduate students to not only build them for flight, but also to build them as engineering models for use in hands-on lab demonstrations and attitude control experiments. Two such attitude control tests that can be done in the lab are also described.

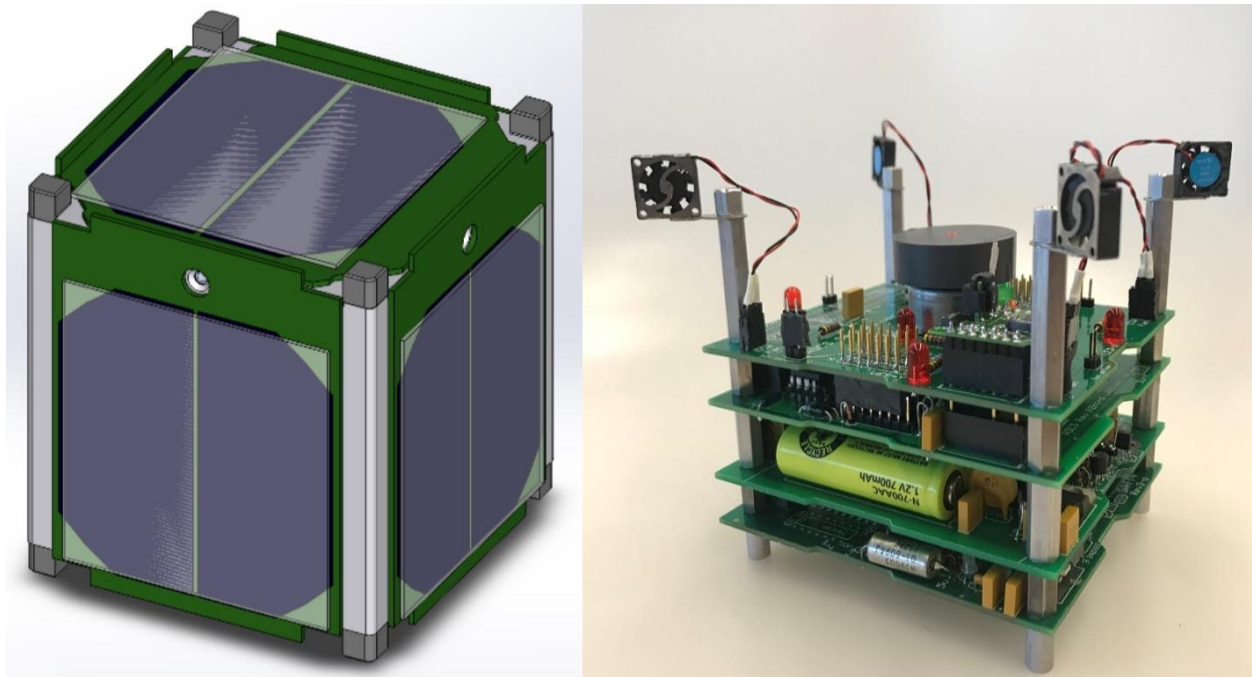


Figure 1. Flight Unit (Left) and Lab Unit (Right)

Structure

PSAT1U's satellite flight and lab units are shown in Figure 1. The satellite was designed for a maximum mass of 1500 g within the 1U frame, and the ability to host additional payloads within about 1.5" in the

board stack. The Electrical Power System (EPS) and physical layout of the satellite were designed to be flexible and provide power for the comms mission and additional payloads.

Electrical Power System (EPS)

Since the size of PSAT1U is reduced by 33% compared to previous 1.5U satellites, the biggest impact is in the solar panel collection area. In this case, only two ZTJ solar cells fit per side, instead of the three cells used in past designs.

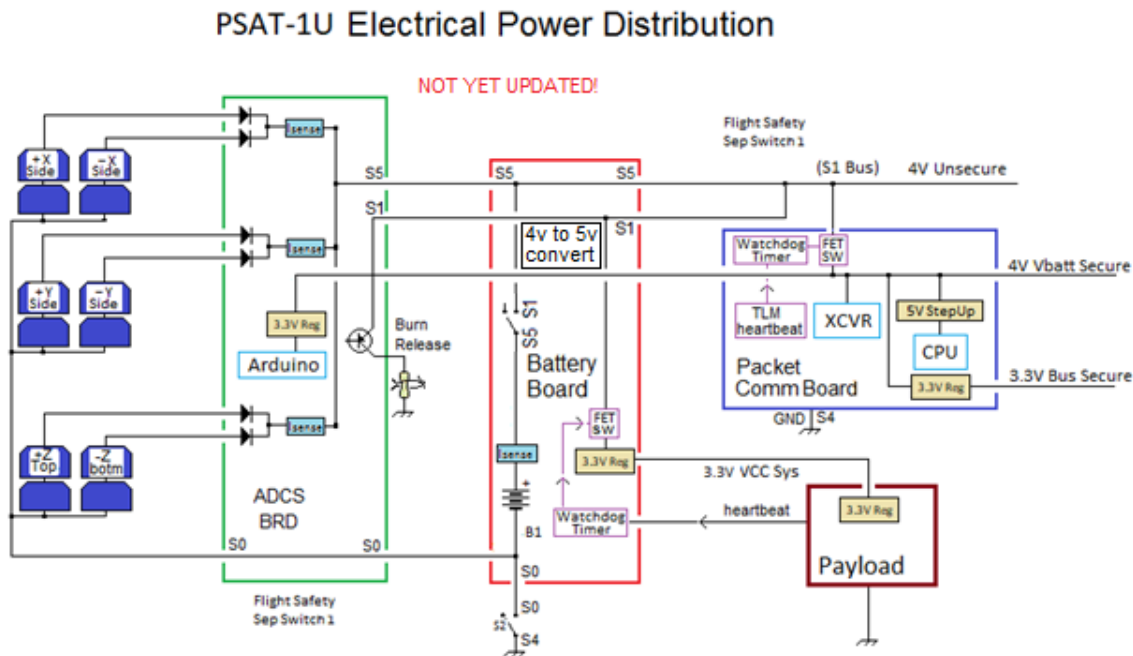


Figure 2. PSAT1U Electrical Power Distribution design diagram.

Solar Cells

For flight, PSAT1U uses factory second ZTJ solar cells, rather than the very expensive UTJ solar cells, offer similar performance at one-tenth of the cost. The ZTJ cells do not include cover glass because of the low cost. Inexpensive thicker microscope cover glass is used as it is 1% of the cost and any added mass increase is insignificant.

ZTJ Solar Cell power output. The ZTJ cells output a maximum current of 503 mA, at a max power voltage (V_{mp}) of 2.41V, giving a power output of 1.21 Watts per cell. In Figure 3, the IV curve has been redrawn to show the actual values for a two-cell side panel, summing to only 4.8 volts compared to the 7 volts on 1.5U CubeSats, offering a peak solar power of 2.42 W.

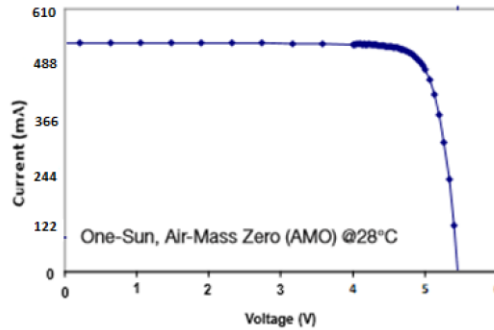


Figure 3. I-V Curve for Two ZTJ Cell Side Panel

Whole orbit power. For a cube satellite, the average total illumination of all six faces, all twelve edges, and all eight corner geometries works out to about 1.4 times the power of a single side. This gives about 3.5 W total average sun power while in the Sun. Reducing that by worst case eclipse times for a typical LEO orbit and battery storage inefficiencies results in a whole orbit average power of about 1.5 Watts average mission power. This does not include additional solar power due to Earth solar albedo, which is kept as a design margin.

Battery Board

Chemistry. NiCd batteries have over 50 years of space heritage and survivability and offer an excellent lifetime survivability. While lithium cells offer higher energy density, they are much less forgiving of abuse and require complex battery management systems on each cell to prevent hazards and failures. Single errors in charging or discharging can destroy the cell permanently. Alternatively, NiCd cells can survive occasional overcharge and complete discharge with negligible damage, making them an ideal low-risk solution for student projects.

Since all past USNA CubeSats have used additional mass ballast to maximize orbit life, there is no need to reduce battery mass in PSAT1U, making NiCd cells a better choice for this application.

To meet peak power demands and provide power in eclipse, PSAT1U's batteries need a capacity of 3.5W for a 30 minute eclipse, or about 1.7 W-hrs. Commercial CubeSat lithium batteries cost \$1900 and require additional components that add complexity. A ready-made 10 W-h lithium CubeSat EPS board costs \$5600. Using NiCd cells, 5.6 W-hrs can be achieved using six 1400 mAh cells at 4 volts and only cost about \$100.

The impact of NiCd use is an increase in volume by three times, and an increase in mass by nearly four times, but only a X% impact on overall The benefit is a 95% reduction in cost while still meeting the power budget and mass limitations. The NiCd cells are 1.898" x 0.543". PSAT1U's battery board design is shown in Figure 4.

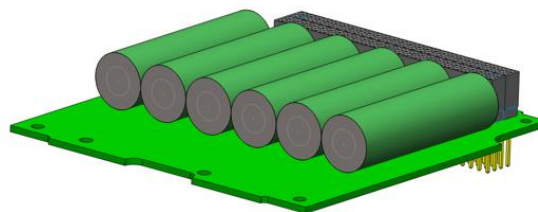


Figure 4. PSAT1U Battery Board Design.

Boost Regulator. Two ZTJ solar cells, summing to a 4.8 V maximum power point, are an excellent charge source for the NiCd battery, but need a DC/DC converter to boost the unregulated 3.6v to 4.2v battery voltage to a regulated 5 volts. The board uses three pairs of parallel 700 mA-h 1.2v AA NiCd cells connected in series to achieve the 3.6v to 4.2v battery bus voltage.

The 5V boost inverter, the Pololu U3V12F5, is shown in Figure 5 with its efficiency and a 3.3v input. When powering only the SATT4 CPU at about 30 mA, the efficiency is around 85%, which then would effectively be drawing 37.5 mA.

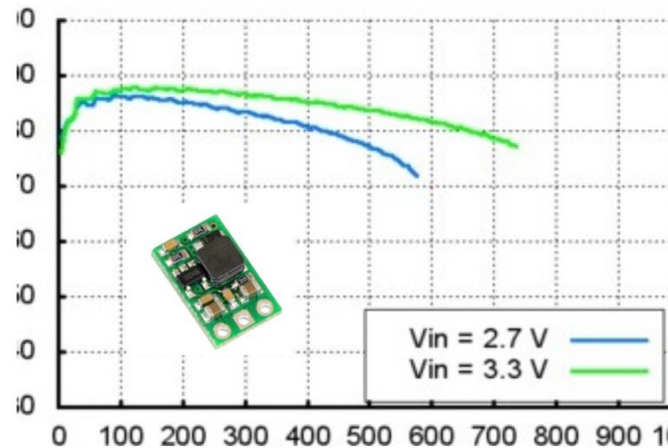


Figure 5. Pololu 3V to 5V DC/DC Regulator Efficiency



Figure 6. PSAT1U Battery Board

Attitude Dynamics and Control Systems (ADCS) Board

Centralized connection board. Because the ADCS depends on sun vector inputs from all solar panels and the ADCS CPU is also used to read solar panel current from each panel, and house the connections to all the torque panels, the ADCS board serves as the central connection point for the solar side panel connectors which contain all these signals and power. This makes it the top board in the stack so that the connections to all the side panels can be made last during assembly.

Diodes and current sensors. When summing current from multiple solar panels, each panel needs an isolation diode. The diode voltage drop for the 1N5819 Shotkey diode is given by the specification sheet as 0.5-0.7 V at 500 mA

In-house experimental testing of the 1N5819 Diode showed performance that was, dropping only 0.4 V at 500 mA. Another 0.16 volts can be obtained if 1N5817 diodes are used.

One current sensor for each axis on the ADCS board measures the the solar cell current for lifetime performance tracking as the cells age. To save A/D telemetry demands, only three current sensors are needed, one for each axis of opposite facing solar panels which are connected in parallel. The ambiguity between whether the positive or negative axis panel is providing power is resolved by looking at the polarity of the sun vector from the sun sensors in that axis.

Arduino Pro Mini microcontroller. The Arduino Programming environment is used for all ADCS and Communication and Data Handling (C&DH) functions. The Arduino Pro Mini can hold up to 30 KB programs, which is more than adequate, since the initial test program for telemetry is only 4.5KB.

Torque coil side panels. Figure 7 shows the side panel for PSAT-1U and highlight the embedded torque coils. The coils are present on both sides of the panel, and each face of the satellite is populated with a panel.



Figure 7. PSAT1U Side Panel (No Solar Cells)

The torque provided by the coil is generated by the equation:

$$T = nIAB\sin(\theta). \quad 1.$$

The total area is found simply by summing the area of each turn in the coil, which results in an average area per coil turn of about 34% of the outer turn (58cm²). This ratio is useful in the torque equations because the average area can be found for any size coil, just by multiplying the area of the largest turn by 34%.

5.74×10^{-7} Nm. This is comparable to the other disturbance forces on the spacecraft in space.

The diagram shows a 555 timer circuit used for a 90-second delay. The timer is configured with a 100k resistor between pins 1 and 2, a 10k resistor between pins 2 and 3, and a 100k resistor between pins 3 and 4. A 1uF capacitor is connected to pin 1. The output of the timer (pin 3) drives a 2N3906 transistor. The collector of the transistor is connected to the gate of an IRF9540 MOSFET. The MOSFET's source is grounded, and its drain is connected to the PTT line. A 'Secure' signal is also shown, which is connected to the PTT line. The circuit is powered by a 5V supply from a DC/DC boost regulator.

The 90 second watchdog timer resets the CPU if it fails to transmit its one-minute telemetry. The FET switch is held on by the 555 watchdog timer and NPN transistor during the timing cycle. If the timing capacitor fully charges (90 secs) then the 555 will trigger a reset which will output low and let the NPN turn off and FET switch to open. This will interrupt the 5v bus on the SATT4 board for about a 2 second power-cycle if ever the 1 minute SATT4 telemetry does not key the transmitter PTT line. Normally, however, the PTT circuit dumps the charge on the 555 timing capacitor so that it never reaches full charge as long as PTT occurs at least once a minute. Notice also that there is a 1uF capacitor in series with the PTT line so it is only a transition of the PTT line that keeps the capacitor discharged. If the PTT happens to latch on, then because of the 1 uF cap, the timing capacitor is not dumped and the system will reset.

Testing. To assume good turn on, each FET is tested to be sure that it has low voltage drop across it when used in this circuit. No more than 0.3 volts is acceptable when providing up to 800 mA to the load.

One batch of 26 FETs were tested with a 5.2 Ω load. The average voltage drop at a 5v supply was 0.27v, with a standard deviation of 0.011v. Another batch of FETs were tested with an average voltage drop of 0.363v, and were not used.

Power Budget

PSAT1U's power budget is shown in Figure 9.

Load	Voltage	Ipk	Duty Cycle	Normal (mA)	Stdby (mA)	ALL ON (mA)
SATT4 RX (StdBy)	5	60	90%	54	54	OFF
SATT4 RX	3.3	120	10%	12	OFF	120
SATT4 TX Tlm	4	750	2%	15	15	750
SATT4 TX users	4	750	4%	30	OFF	OFF
Arduino CPU On	3.3	5	10%	1	OFF	5
Arduino CPU sleep	3.3	2	90%	2	2	OFF
Payload Stdby	3.3	-	-	-	-	-
Payload OP	3.3	-	-	-	-	-
Totals				113	71	946

Solar Current per Panel=	503.085 mA	Avg Capacity Produced Per Orbit	599.55 mAh
Average Current from geometry=	712.55 mA	Avg Capacity Consumed Per Orbit	56.5 mAh
Current Margin (Stdby)*	432.085 mA	Capacity Margin	543.05 mAh
Current Margin (Normal)*	390.085 mA		

* Margin Calculated Assuming Single Panel Power Production (minimum)

Time (min)
Eclipse: 30
Daylight: 60

Figure 9. PSAT1U Power Budget.

An orbit eclipse time of 30 minutes was assumed in the power budget calculations. The power budget accounts for three different mission modes. These include normal operations mode, standby mode, and safe mode. The budget also accounts for four different loads, the SATT4 communications board Receiver, SATT4 communications board Transmitter, the CPU, and a potential payload.

Attitude Dynamics and Control System (ADCS)

Magnetometers and sun sensors provide the attitude determination roles on PSAT1U. The ADCS board is shown below in Figure 10. Several mission modes can be programmed into the board, including free float, Bdot, constant spin, and an experimental sun-pointing mode. The experimental sun-pointing mode is not actually required in PSAT1U because each side provides equal power and can operate well in any attitude, but it does provide academic experience.



Figure 10. ADCS Board Model.

Attitude control for flight uses magnetotorquer coils. These coils are built into the solar cell side panels. Each coil has a dipole moment of 0.0046 Am^2 . There are four coils on each axis which provides 0.0184 total dipole moment, and at a magnetic field of $3.09 \times 10^{-5} \text{ T}$, the maximum torque provided will be around $5.74 \times 10^{-7} \text{ Nm}$. The torque coil design is shown previously in Figure 7 of section 3.3.4.

Communications System

Communications Board

PSAT2's communications board is a 1.5-Watt APRS transceiver operating in the 2-meter amateur radio band. Its processor supports these capabilities:

- A Digipeater function to relay user packets from uplink to downlink
- Five external analog inputs compatible with most TNC analog telemetry.
- 8 digital output bits that can be toggled under-ground control for spacecraft functions.
- A serial port for uplink and downlink between other boards and the ground
- A transistor on/off power control line (originally used as a GPS power control in terrestrial applications) that can be used for possible other satellite functions.

SATT4 Dual Bank Switching. The SATT4 can be programmed with two separate operating configurations or banks as detailed in [Appendix D](#). The main use of this feature on most of our CubeSats is to enable and disable user digipeating (packet relay) and to switch the uplink receiver to a separate frequency if needed for the payload experiment. The configurations in Bank0 and Bank1 are switched on the condition of the JP1 bit. Unfortunately, this is also the 5th Telemetry channel input. See the telemetry section to see how this bit is shared between commanding and Temperature sensing.

SATT4 Communications Board. The SATT4 communications board block diagram is shown in Figure 11. The physical USNA SATT4 board is shown in Figure 12.

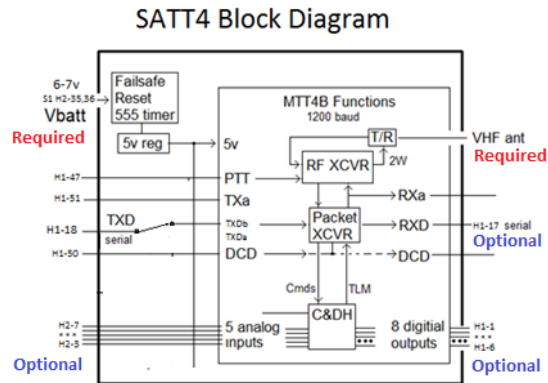


Figure 11. SATT4 Communications Board Block Diagram.



Figure 12. USNA SATT4 Communications Board.

SATT4 Bus Voltage Considerations. The SATT4 board's watchdog timer runs on the 5V bus and powers everything on the SATT4 board as long as the watchdog timer does not time-out due to lockup of the SATT4 one-minute telemetry.

The board's transceiver will operate on the 4V Vbatt secure line to provide the maximum RF power directly to the transmitter without loading down the DC/DC boost regulator. This voltage does not need to be regulated because the RF transmitter is the highest load on the satellite and only varies output power slightly on unregulated power.

The current required has been measured to be about 30 mA at 5 V. Considering the 85% efficiency of the converter, this equates to about 40 mA on the 4 V bus.

SATT4 Inputs and Outputs. The SATT4 has 5 analog channel inputs for as shown here. These 5 channels are transmitted to the ground in the once a minute telemetry packet:

PSAT2>APRSAT,ARISS:T#SSS,111,222,333,444,555,10101010

The telemetry packet begins with the SSS serial number (one per minute), then the five channels, and ends with eight 1/0 bits on the end of the telemetry indicate the state of the 8 discrete command bits. Two of these are used internally, but six are available for hardware command purposes. They can be commanded high or low.

Analog Telemetry Port SATT4

1. GND
2. VCC
3. PA3 Ch 5 T batt (and bank SW)
4. PA4 Ch 4 Temp Z-
5. PA5 Ch 3 Temp Z+
6. PA6 Ch 2 System Load Current
7. PA7 Ch 1 7v bus Voltage
8. +5 Volts

I/O Port C bits: (needs confirm)

1. GND
2. PC0
3. PC1
4. PC2
5. PC3
6. PC4
7. PC5 \$20 bit to bank/sw PA3(JP1)
8. +?7 volts VCC?

The Vin voltage telemetry on CH1 is wired to the S1 bus connection H2-35/36 so that it can read the battery voltage directly.

Configuration Bank Select: First, notice that the logic of the Bank Select is reversed. When the bit is pulled to ground with the \$00 command the bank is switched to Bank1. When it is left floating or high with the \$20 command then the default Bank0 is selected. For command purposes, we want to invert this, to have the default bank be SAFE (with user digipeating off) and have it asserted with the \$20 command to turn it on.

To do this we bias the bit low with the XCVR thermistor in parallel with a 27.4k resistor by default to keep it in Bank1 (active-low) which is now configured for safe mode and no digipeating. Then we strap the \$20 bit to this pin via an 8.25k ohm R1 pullup resistor so when \$20 goes high it switches to Bank0 (the default) and the thermistor works as a normal R1/R2 divider. This makes the operational shift to DIGI-ON mode be \$20 TRUE logic. This matches all other \$XX command bits. Here are the two states:

Default: Bank1 - PSAT2-1>APSAFE: Uplink on 145.980, SAFE or DTMF ops and no BTemp

\$20 cmd: Bank0 - PSAT2 >APDIGI: Uplink on 145.825, digi ON, TLM Ch5 is good

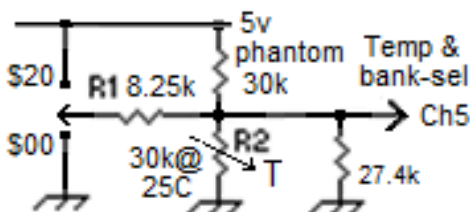


Figure 13. Thermistor Schematic

The 27.4k and series 8.25k resistor are used to bias the thermistor so that it can still give temperature telemetry even when the bit is also used for Bank-select. Note, that the thermistor is in the ground leg (saves having 5v to all thermistors) and this inverts the sense of the A/D values and high temps give low counts and low temps give high counts.

SATT4 Telemetry Formats. Payload data formats can be anything defined by the payload and sent to the SATT4 on the serial input for transmission. The telemetry packet format for the SATT4 has already been defined above. But there are two other fixed formatted beacon packets that can be programmed into the SATT4. These are the BText and LText:

SATT4 telemetry: PSAT2>APRSAT,ARISS:T#SSS,111,222,333,444,555,10101010

SATT4 Beacon: PSAT2>APRSAT,ARISS:US Naval Academy, W3ADO

SATT4 Ltext: PSAT2>APRSAT,ARISS: whatever you want goes here...

SATT4 Serial Communication Ports for AUX payloads. The SATT4 has two serial ports for auxiliary processors, both transmitted in the same format. The receive or uplink packets appear on the RXD lines and contain all raw packets heard on the channel so that individual payload CPU's monitoring that line can listen for unique commands sent from their ground stations. The RXD data line idles high and it is pulled low at TTL levels at 9600 baud when packets are received. It can drive several TTL loads for any CPU monitoring for data. Remember, the actual data RF channel, though, is only at 1200 baud AX.25. Similarly, the TXD data line of these ports will accept 9600 baud serial ASCII formatted data from any auxiliary payload CPU and

transmit it to the ground using the SATT4's existing header: [e.g., PSAT2>APRS,ARISS:] In this case, to share the line from multiple sources, the SATT4 input is TTL and is idling high.

Any CPU with data then sends the data in TTL levels via an NPN Pulldown Transistor. There is no handshaking so these CPU's should not hog the line and should keep all transmissions brief. Again, anything over about once a minute is excessive unless it is in response to immediate ground command. The CPU must format the data so that it is recognized by its intended recipient distinct from any other traffic. All ASCII text ending in a CR will be transmitted in one packet. Typical data lengths should be kept to about 72 characters or less and the format should use only PRINTABLE ASCII characters, for compatibility with the worldwide APRS ground station network. It is possible to transmit multiple short lines in one packet if the "pass" byte is used before each CR (except the last).

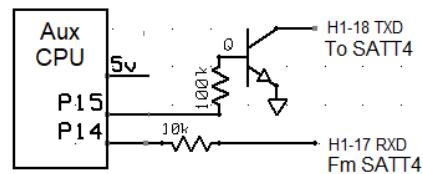


Figure 14. Serial Port Schematic

Antenna Design

PSAT1U uses VHF packet radio communications for both telemetry and command and control on 145.825 MHz. A VHF monopole wire antenna about 724 mm in length appears to give the lowest SWR in the EZNEC model. This is longer than a typical $\frac{1}{4}$ monopole because the cubesat frame counterpoise is so small. Our designs typically use a pair of orthogonal whips for cross polarization.

The multiple cubesat antennas are wrapped around PSAT1U's body from their various drive points to all arrive at a single point where the burn resistor can be located. A nylon fishing line holds the antenna whips in place until the burn resistor burns through the nylon string, releasing the antenna. The body wrapping and burn resistor design concepts are shown in Figures 15 and 16, as incorporated on a previous USNA small satellite.

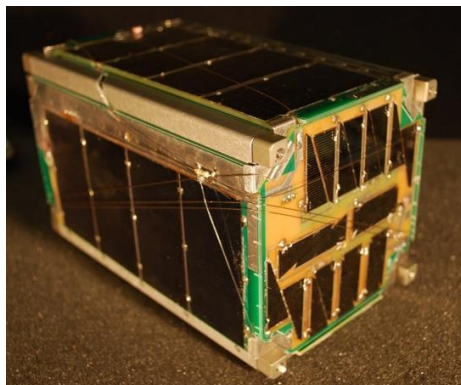


Figure 15. Body Wrapping Concept for Antenna.



Figure 16. Burn Resistor ??? antennas on PSAT.

Payload

PSAT1U can host a variety of different payload experiments in the allowed volume as displayed in Figure 17.

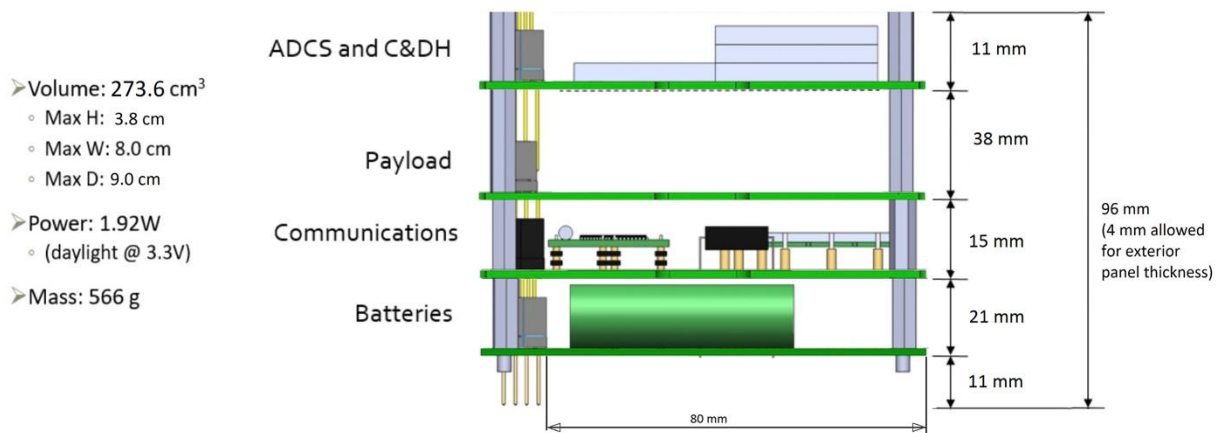


Figure 17. PSAT1U Payload Maximums.

Auxiliary payloads must have a mass less than 560 g and a maximum volume of 240 cm³. Specifically, payloads are allowed a maximum height of 3.8 cm, maximum width of 8.0 cm, and maximum depth of 7.7 cm. Payloads should operate within the available on-orbit average power of 1.9 W, operating at a voltage of 5V. The bottom height measurement can be reduced if needed by cutting the ends of the headers on the bottom board flush and finding alternate placements for separation switches. This could allow up to 9 mm of extra height for the payload, totaling to 4.7 cm and a volume of 340 cm³.

LabSat Attitude Control Board

For operations in the lab, and more importantly to be able to demonstrate attitude control, a special Attitude Control Board (ACB) can be built. The ACB sits as the top board on the PSAT1U structure in place of the top solar panel. The ACB includes two thruster fans, a reaction wheel on one axis, and the existing magnetic torque coils, controlled by the Arduino on the ADCS board.

Design

The overall schematic for the ADCS LabSat board is included below in Figure 18.

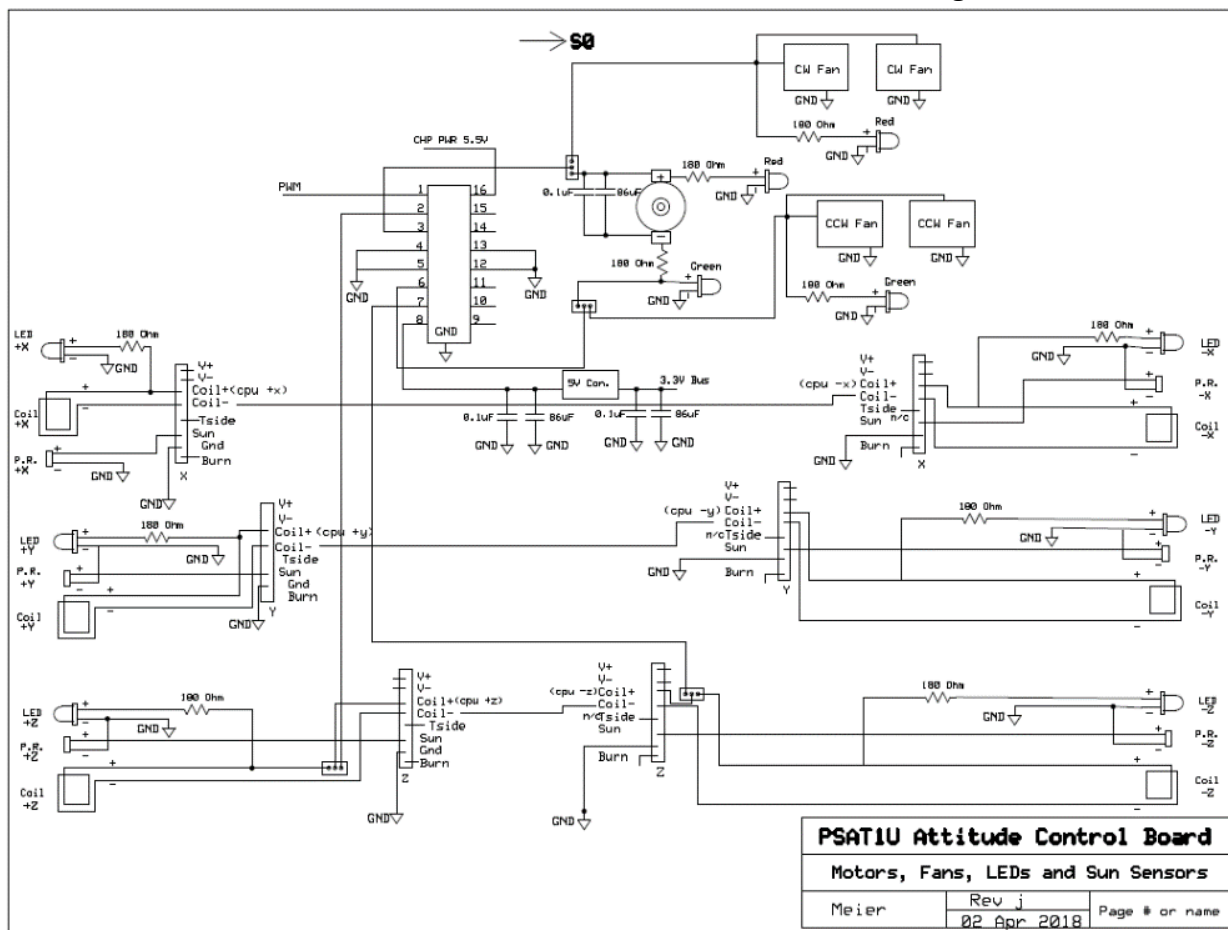


Figure 18. PSAT1 ADCS LabSat Board Schematic.

As seen in the schematic, the classroom ACB includes an “H” bridge driver chip, a reaction wheel motor, fans, LEDs, sun sensors, and photoresistors. Incorporating all of these components on a small LabSat board allows students to learn about ADCS while working with a satellite of accurate form factor for flight-ready CubeSats.

Assembled Structure

Figures 19 and 20 show the final product of PSAT1U with the LabSat payload board atop it.

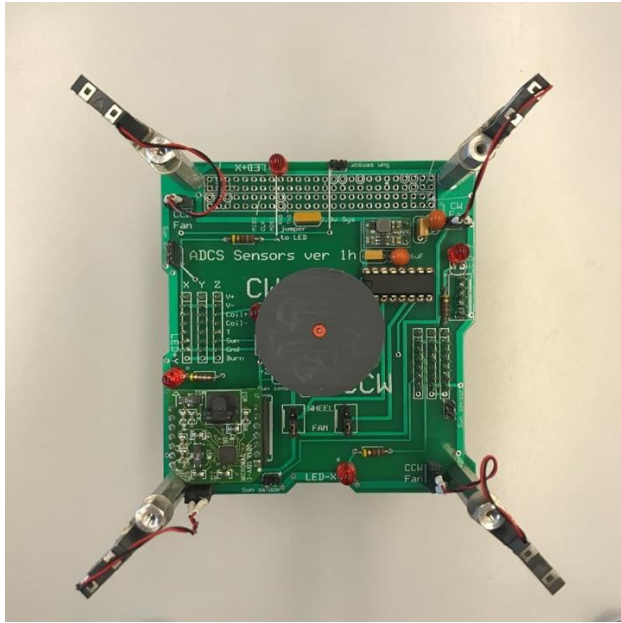


Figure 19. Completed LABSAT Module

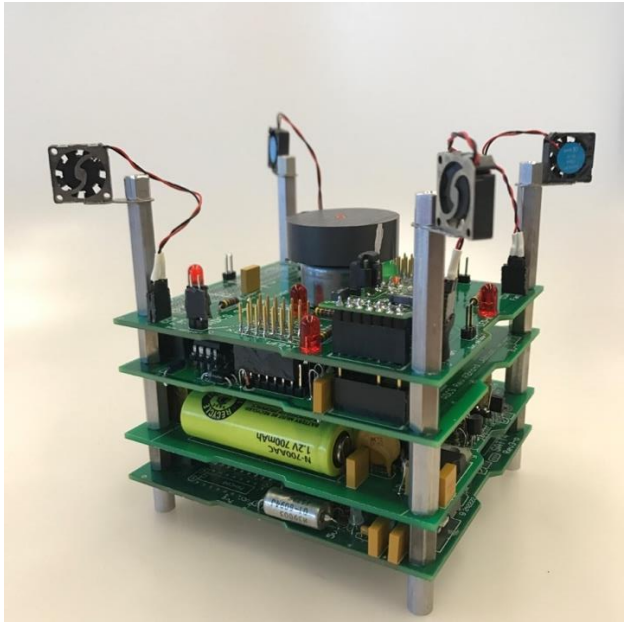


Figure 20. Completed PSAT1U with LABSAT module installed

Attitude Control Testing

Dynamic ADCS testing. A simple test/demo system for a model CubeSat is shown in Figure 21. First, on the shelf below the satellite, (not visible) magnets were placed in specific locations to cancel out the Earth's magnetic field as reported by the satellite. Then, a magnet was suspended by a strip of paper (visible on the right) hanging on an arm balanced on the rotating knob of a dark room timer. The length of the arm was adjusted to simulate the Earth's magnetic field at the satellite.

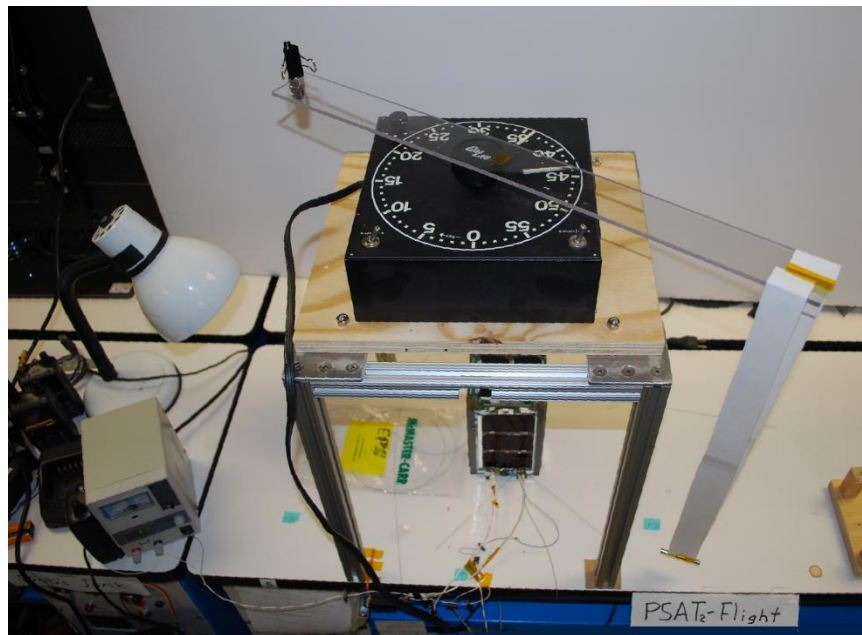


Figure 21. Poor man's ADCS Test set. Notice the magnet on the right suspended from an arm rotating at 1 RPM by the dark-room timer motor.

To test the dynamic response of the CubeSat, the timer rotates the magnet at 1 RPM, simulating the spacecraft rotating in the opposite direction. For this demonstration, each of the torque coils on the side panel had an LED illuminated when the torque coil is energized. This made it possible to visually interpret the reaction of the satellite in its various ADCS command modes. This simple test setup was invaluable over several days in giving us confidence that everything was wired with the correct polarity and the ADCS CPU was commanding the right torque coil response.

In the same Figure 21 you can see the 6 foot HF wire antenna coiled up in the McMaster-Carr plastic bag and the two UHF right angle crossed polarized whips coming off the front. The pair of two-meter 20” whips are not visible. The umbilical wires all have ferrite beads and chokes on them to prevent RF from getting in to the control lines. As each axis has four separate torque coils, this test was important in making sure that they were all working together in the right direction. This is done by holding a compass near the coils as the magnet swung around the CubeSat and activated the various attitude control modes.

Another lab test setup that gives even better flight simulation is the Frictionless Suspension Test System.

Frictionless Suspension Test System (FSTS)

The Frictionless Suspension Test System can test satellites in an isolated rotational degree of freedom in the Z axis. By hanging a satellite from the string connected to a stepper motor, the motor can closely mimic the position transmitted from a sensor on-board the satellite. In this way, the stepper motor can follow the satellite’s position so that there is minimal external torque applied from any small errors between the suspension hook and the satellite due to the long support string. By hanging the satellite about a desired axis and “shadowing” its position with the support string, its dynamics can be tested in that rotational degree of freedom.

Any disturbance torques in the FSTS can be an order of magnitude less than any air bearings or other apparatus and are down on the order of those that might be experienced in space. Even at low speeds, air bearing systems still introduce non-negligible amounts of friction and disturbance torques due to the turbulence of the air flow through the bearing, no matter how well it is machined. However, the FSTS has the advantages of low cost and simplicity.

Description

For the communication link between the satellite under test and the FSTS suspension stepper motor controller, either the satellite’s existing telemetry and ground station can be used, or an XBee transmitter and magnetometer on a sensor board can be used. The Satellite or sensor board sends azimuth data every half-second. It is very important that the initial alignments are correctly calibrated before use. A recalibration is required any time the FSTS is moved due to the Earth’s



Figure 22. FSTS structure.

varying magnetic field and the influence of surrounding structures and objects. The user should also be conscious that large current-carrying electronics and ferromagnetic objects can create near-field disturbances to the calibrated magnetic field, causing a faulty determination of azimuth by the Sensor Board.

When the FSTS Electronics Board receives the azimuth data from the Satellite or Sensor Board, it determines the error between its current position and the new position of the satellite being tested and commands the stepper motor to turn to the updated position in the correct direction.

The Liquid Crystal Display (LCD) displays the position of the satellite and the motor during testing, as well as a numerical determination of the satellite's rotation rate.

Display. Once the system is aligned in the desired direction and the start button is pressed, the LCD begins to output the satellite's azimuth, the motor's azimuth, the satellite's rotation rate, and the average rotation rate. The rotation rate is measured as: $\omega_{avg} = 0.9\omega_{avg} + 0.1\omega$.

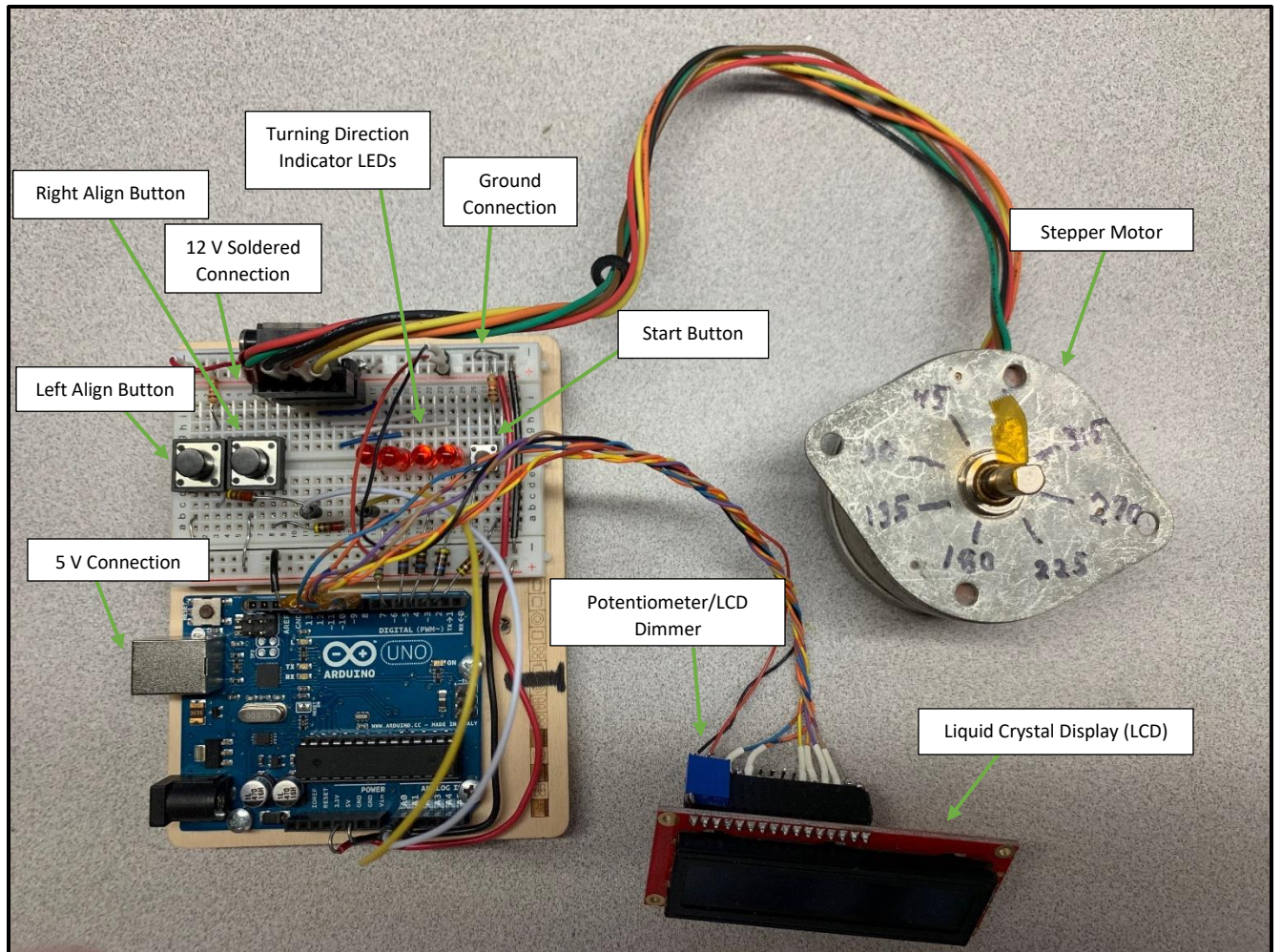


Figure 23. FSTS Motor Electronics Board, display, and motor.

Initialization

The user must first align the satellite pointer with the stepper motor pointer by manually adjusting the swivel joint just above the satellite hook. Then the program is started, and the user is prompted to press a button once the pointer on top of the FSTS and the satellite are aligned. Upon the press of the button, the motor's position is initialized to equal the satellite's azimuth. The long support string ensures that the error between the motor azimuth and the test satellite's azimuth will impart negligible torque on the test satellite.

Motor control. The 12 V Airpax stepper motor can be stepped in $\frac{1}{2}$ steps to achieve 3.75° precision rather than whole step 7.5° precision. This allows better precision to shadow or mirror the test satellite's azimuth.

Characterizing the friction in the system. A detailed analysis of disturbance torques on a CubeSat is covered in [4]. The total worst-case disturbance torque was estimated to be 1.1×10^{-6} Nm. To find the maximum allowable offset error between the support motor and the satellite, the torsional spring constant of the 53" (1.36 m) long string, measured by comparison to the half period of a cylinder of known inertia, where:

$$I = \frac{1}{2}mr^2 = 0.0011123 \text{ kg} \cdot \text{m}^2 \quad 2.$$

Next, we wound the string up 3 turns and released it, noting the time for period as $T = 100.12 \text{ s}$.

Then, the angular frequency for the system was found by

$$\omega_n = \frac{2\pi}{T} = 0.06283 \text{ rad/s} \quad 3.$$

Finally, the spring constant, K , was found by

$$K = I\omega_n^2 = 1.532 \times 10^{-7} \frac{\text{N} \cdot \text{m}}{\text{deg}} \quad 4.$$

With this spring constant, the FSTS could have an error of up to 7.2° (difference between the test satellite's azimuth and the motor azimuth), and still apply less torque than the worst-case in-space disturbance torque, of $1.1 \times 10^{-6} \text{ Nm}$. Furthermore, since the side torque coils on the Naval Academy's PSAT2 can generate between 1.3×10^{-6} and $3.1 \times 10^{-6} \text{ Nm}$ of torque, or up to three times the worst-case disturbance torque, then this error can be offset. Thus, the FSTS can allow near zero-gravity environment simulation.

Testing

To verify the FSTS's successful reduction of friction, an **X** kg satellite with a measured MOI of 0.00616 kg m^2 was used.

The first test was conducted without the FSTS system activated. The satellite was given an initial push at a rate of about $30^\circ/\text{s}$. The satellite's average rotation rate, as seen on the LCD, was recorded every five seconds until the rate slowed to zero and the board began to spin in the other direction. This test established the baseline without the FSTS. Next, tests were done at multiple initial rotation rates for three minutes. Again, the average rotation rate was recorded every five seconds. The results for all five tests can be seen in Figure 24 below.

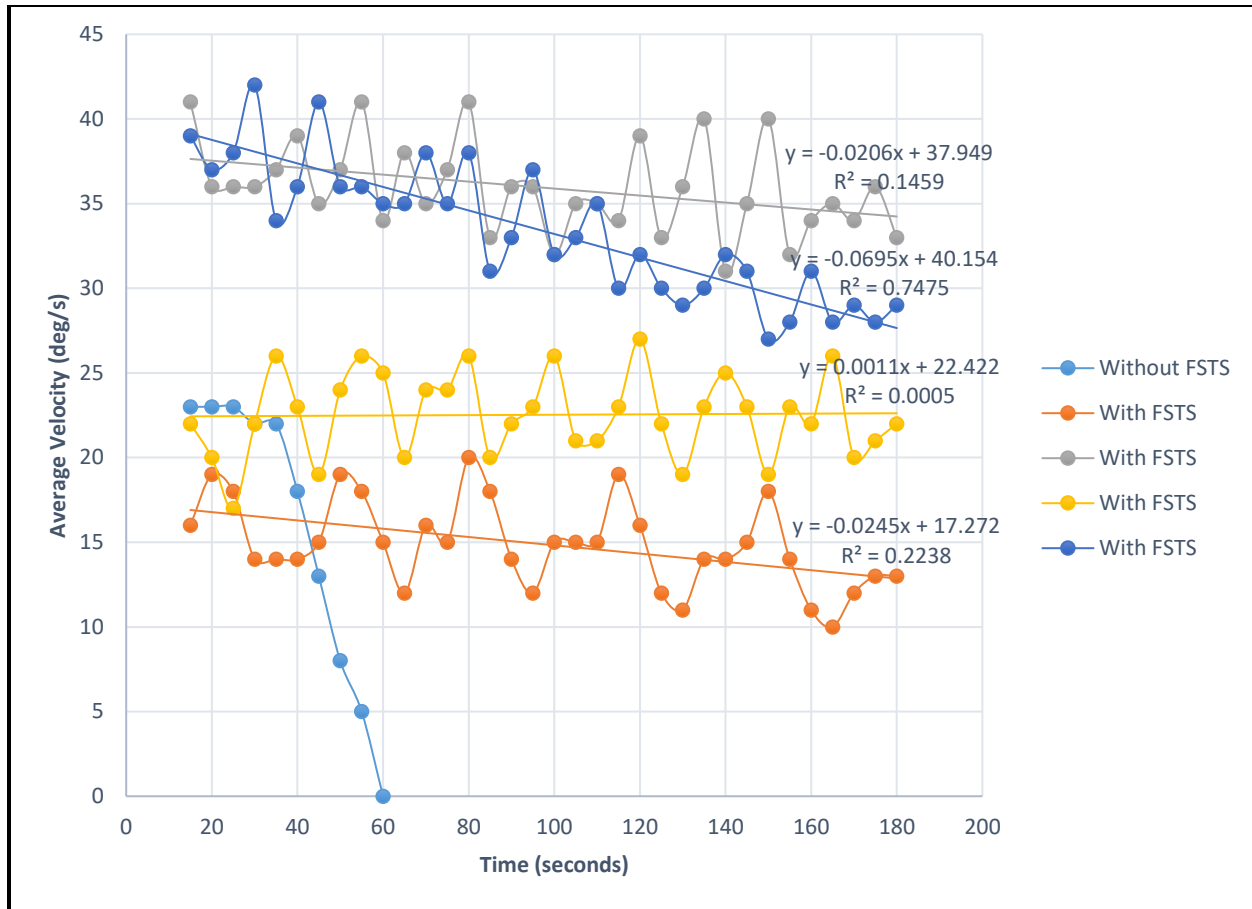


Figure 24. Testing the effectiveness of the FSTS.

As is seen in Figure 24, activation of the FSTS drastically reduces rotation decay and allows for continuous rotation. To determine how long the system could operate, a longer test was done over 25 minutes. The plot of the average angular velocity is seen below in Figure 25. The steady decay is an indication of the decelerating satellite. Next, the question was how much of the deceleration was due to FSTS friction, and how much was due to aerodynamic drag.

In this test, the pointer at the bottom of the string was allowed to settle once the satellite was hanging. Once the satellite was completely still, the starting azimuths of the motor and the Sensor Board with the metal plate were recorded. In the test, the motor started at 000° , while the Sensor Board was pointing at 285° . After recording the azimuths, the FSTS Electronics Board was commanded to spin the satellite at a constant rate of $30^\circ/\text{s}$. After about 15 minutes, when the string torque and aerodynamic torque were given ample time to reach steady-state, the data collection began. Recordings of the satellite position were taken every time the motor passed north. The average azimuth of the satellite after 123 passes was 299° . This corresponds to a 14° average drag offset. Using the string's torsional spring constant, we estimate the aerodynamic torque to be $6.15 \times 10^{-5} \text{ Nm}$. Since this is an order of magnitude larger than any torque on the satellite expected from the error between the motor and satellite position, then the limiting factor for friction in the FSTS is aerodynamic drag and not the error in the system itself.

Using the Sensor Board and metal plate's combined MOI, an estimate for the aerodynamic deceleration of the satellite is made as

$$\alpha = \frac{\tau}{I} = \frac{-6.15 \times 10^{-5} \text{ N}\cdot\text{m}}{0.00616 \text{ kg}\cdot\text{m}^2} = -1.0 \times 10^{-4} \frac{\text{rad}}{\text{s}^2} = -0.0572 \text{ }^\circ/\text{s}^2 \quad 6.$$

Since this value is on the same order of magnitude as the linear fits in Figure 24, we know that this deceleration estimate for a satellite spinning at 30°/s is reasonable.

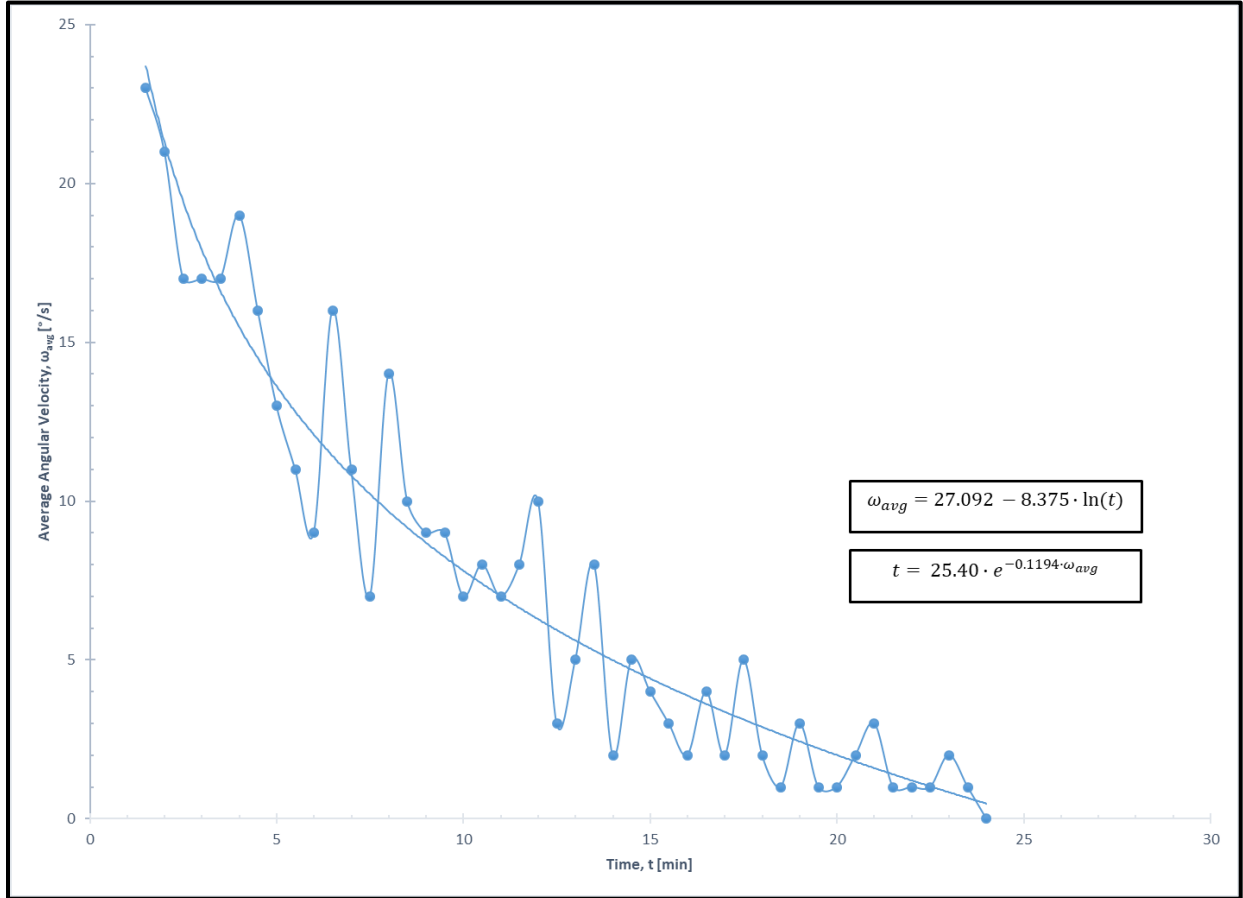


Figure 25. Angular deceleration during testing.

Since the FSTS imparts less torque on the system than the typical disturbance torque of 1.106×10^{-6} Nm experienced on-orbit, then it is a viable test environment. Satellite dynamics can be tested for tens of minutes, simulating a low-altitude orbital environment. Finally, since the error torque due to the lagging stepper motor is less than the aerodynamic drag torque of 6.15×10^{-5} Nm, then the FSTS effectively minimizes the external torque applied to the satellite during testing. Therefore, this system is a very low-cost way to simulate an orbital environment in one rotational degree of freedom.

Cost Budget

Item	Description	Vendor	Qty	Unit Price	Extended Price
1U CubeSat Chassis	Skeleton Chassis	Pumpkin	1	\$1,400	\$1,400
Solar Cell	ZTJ Bare Solar Cells	SolAero Tech, Inc	12	\$50	\$600
Cover Glass	36/pkg	Ted Pella,	1	\$165	\$165

		Inc			
ADCS Board	Magnetotorquer boards	Student Built	1	\$200	\$200
Battery Cells	1.2V 700mAh NiCd	Digi-Key Electronic	6	\$2	\$13
Comms Board	SATT4	Tiny Trak	1	\$400	\$400
Battery Board	Battery Board	-	1	\$50	\$50
Antenna	Wire Monopole Antenna	-	1	\$10	\$10
3V DC Motor	RF-300FA-12350	FastTech	1	\$4	\$4
				Total:	\$2,842

Table 1. Cost Budget

References

O:\EA469-470\2017-2018\PSAT1U\ADCS\Documentation\Reaction Wheel Design Document-d.docx

O:\EA469-470\2017-2018\PSAT1U\Comms\Comms Documents\PSAT1U-comms-design-c.docx

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Cells\Documents\PSAT1U_SolarCell_Design.docx

O:\EA469-470\2017-2018\PSAT1U\EPS\Solar Cells\Documents\Testing\Thermal Performance on Solar Cell

i

Comparison of Omnidirectional VHF Antenna Construction and in situ Performance for LEO Satellites

Gerard Anandappa, KD9NNU
Abdus Saboor Zubair, KD9NNV
Dan White, Ph.D., AD0CQ

Abstract

Lowering the barriers of entry with regards to building a satellite ground station is central to why a comparative analysis of easy-to-build antennas is needed. Easing access to the experience of setting up a ground station and observing passing satellites is a valuable asset to any community, and allows those who are interested in the data being transmitted, more opportunities to receive said data. The study compares the receive performance of two omnidirectional VHF antennas. Antenna performance metrics include SWR, return loss, decoded images, impedance in the VHF band, and more. Understanding which antenna performs best

with minimal tedium during setup can be accounted for as a significant barrier lowering factor. As such, the study also compares the ease and practicality of each antenna build, considering skill level, cost, access to materials, and other relevant factors. The antennas under test include the crossed-dipole and quadrifilar helix (QFH), both of which are omnidirectional VHF and relatively easy to build. Both of these antennas were to operate in the two-meter band, between 146-148 MHz. Preliminary results suggest the QFH receive performance is stronger than the crossed-dipole.

Background

Assessing antenna performance and constructability are the fundamental criteria by which completion of our objective will be measured, therefore, the ensuing analysis considers the performance of two antennas operating in the two-meter band that were constructed using materials purchasable at any hardware store and tested using a VNA as well as other equipment and techniques. A quantitative comparison of homemade, LEO reception antennas is not present in any existing published material, therefore, data acquisition for the purposes of comparing the antennas had to be done. This was accomplished by ensuring that both antennas operated in the same conditions, these include location, environment, builders, measuring devices and receive parameters such as gain, orientation in space, and reception frequency.

The missions of SatNOGS, an open source hardware platform for networking satellite ground stations, the Libre Space Foundation, and our own objective of accessibility informed our choice of which antennas to build. To be in compliance with our objective, the chosen antennas had to be omnidirectional, as this is the most cost effective, and require minimal construction experience on the part of the builder. Thus, the chosen antennas were

the crossed-dipole or turnstile antenna and the quadrifilar helix (QFH or QHA) antenna. Our intended receive frequency was to be at 146 MHz. This frequency would allow us the flexibility to downlink data from the NOAA weather satellites at 137 MHz, the Fox satellites, and many others operating in the two-meter amateur band.

Crossed-Dipole – Characteristics & Construction

The first antenna to be considered will be the half-wave crossed-dipole (or turnstile) antenna. The materials needed for construction included 1¼” PVC, 13 feet of ¼” aluminum rod, ¼” nuts, ring terminals, terminal blocks, LMR-195 coaxial cable, and terminating coaxial connectors. The desired reception frequency of 146 MHz dictated the length of each half of the dipoles to be 18.4” and reflectors to be 36.94”. The construction process consisted of creating four through-holes perpendicular to each other in the PVC pipe through which the halves of the driven elements were secured. Then, four more holes were drilled into the PVC, a quarter wavelength or 18.4” from the driven elements; each pair of holes were drilled in planes offset by a quarter-inch such that the two reflectors could pass through the PVC without coinciding. Next, the driven elements had to be wired. This was done by

separating the inner and outer conductors and connecting them to the driven elements 180° apart. Then, the 90° phase line was cut to 18.4", where one end was spliced with the feedline and the other end was connected to the remaining driven elements [1]. The manner in which these connections were made resulted in the intended left-handed polarization [2]. The challenge of this build was with respect to the congestion of the feed point. Feed point congestion, as seen in Figure 1, is a challenging problem to remedy because antenna theory requires that the dipole is continuous from end to end despite the obvious impossibility of this in reality. Perhaps, the feed point could be a separate assembly which could be coupled to the main post in future builds.

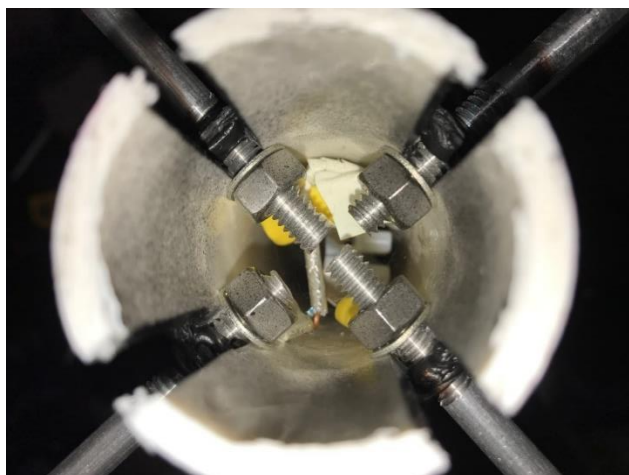


Figure 1: Crossed-dipole feed point

Crossed-Dipole – Performance

Antenna elements for the turnstile were tested with a VNA at particular steps during the building process. Since a turnstile is comprised of two dipoles 90° out of phase, each dipole was tested to verify if it was working at 146 MHz. For the first dipole to undergo VNA testing, the VNA plot of return loss vs. frequency revealed a dip at 138.4 MHz instead at 146 MHz. This result provided the realization that theoretical conditions make assumptions that cannot be ignored in application; frequency has a linear relationship with the length of the dipole, hence the concept of proportionality was used to make the dipole resonant at 146 MHz. I was determined that the dipole should be shortened by 5.2% after calculating the percent difference in the frequencies. After cutting down the length, the dipole was tested again with the VNA, and

successfully obtained a dip at 146 MHz. Then the cross dipole was cut to the same length and verified with the VNA to ensure resonance at 146 MHz. After adding the quarter wavelength phase line and reflector the newly assembled turnstile was tested. The return loss vs frequency plot for the turnstile revealed a dip at 146MHz. Although the dip's position was right, it was not as deep as the dips of the individual dipoles. The return loss was -6.73 dB, as seen in Figure 2, for the turnstile, while the dips of individual dipoles were -27.09 dB. SWR for the turnstile at 146 MHz was 2.71; whereas, resistance and reactance at 146 MHz for the turnstile were 31.2 Ω and 36.4 Ω respectively. After this we scheduled observations through SatNOGS for weather and amateur satellites to obtain the waterfall spectrum and decoded images.

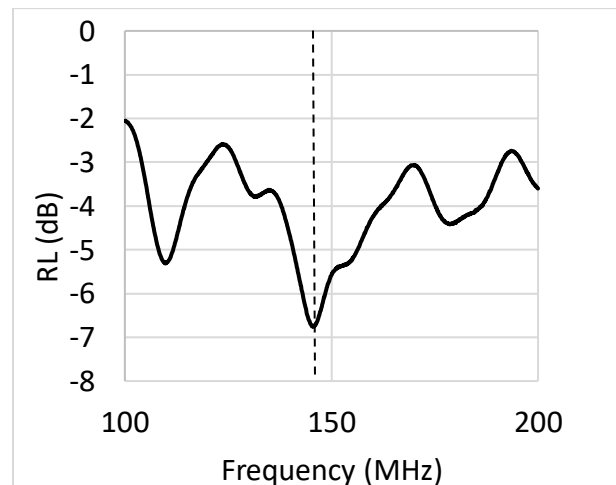


Figure 2: Measure of turnstile return loss over 100 MHz frequency sweep (dashed line denotes 146 MHz).

QFH – Characteristics & Construction

Constructing the QFH antenna was done by following instructions written in the journal QST by David P. Finell, N7LRY, titled *Build a 2-Meter Quadrifilar Helix Antenna* [3]. The materials required for this build included 2¼" PVC, 2" PVC, 2¼" to 1¾" adapter, 2' of ¼" aluminum rod, 12' of ½"-width aluminum strips, ¼" nuts, and ring terminals. The desired reception frequency of 146 MHz dictated the physical parameters of the antenna, like helix diameter and length. Two sets of four holes were drilled 18.4" apart, this set the length of each helix. The helices were made by cutting two 10" aluminum rods and securing them to

each end of two of the aluminum strips. This formed a rectangle which was then twisted by stepping on one end of the assembly and turning the other end 180° by hand. This formed one of the helices, and was repeated to form the other helix. The feed point of the antenna consisted of a 1" PVC cap which was affixed concentric with a coupler at the bottom end of the helix, as seen in Figure 3. Each of the conductors of the LMR-195 coaxial cable were then separated and connected to the elements 90° offset from each other. A 90° phase line was then spliced to the feedline connections on one end, and connected to the remaining two elements on the other end. The challenge in constructing the QFH had to do with screwing the nuts onto the aluminum rods onto which threads were cut using a tap and die set. The softness of aluminum would yield to the hardness of the steel nuts when screwed on, this made fine adjustments of the nuts (which maintain the helix diameter) difficult.



Figure 3: QFH feed point assembly

QFH – Performance

The QFH cannot be assembled in a piece-wise fashion as the turnstile was, so the QFH was tested only once everything was assembled. Once the QFH was put together, it was tested with the VNA. The return loss vs. frequency plot revealed a dip of -6.08 dB at 146 MHz, as seen in Figure 4. Also, the .csv file from the VNA test revealed a real impedance of 18 Ω , SWR of 2.97, and a reactance of -12.5 Ω . The impedance matching technique of using

a choke balun apparently did not prove to be very effective. After the VNA testing, observations were then scheduled through SatNOGS for weather and amateur satellites to obtain the waterfall spectrum and decoded images.

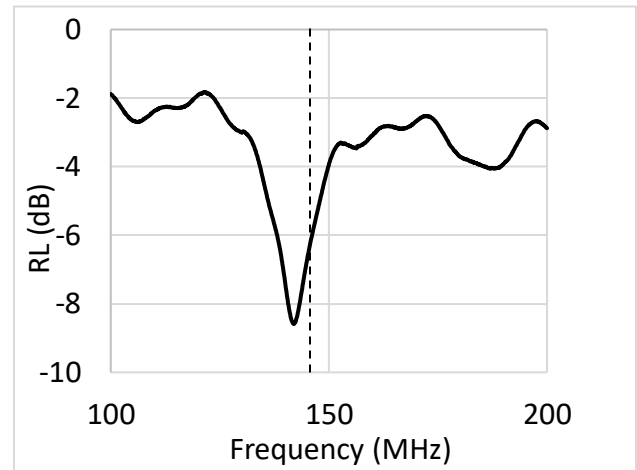


Figure 4: Measure of QFH return loss over 100 MHz frequency sweep (dashed line denotes 146 MHz).

The waterfalls in Figures 5a and 5b illustrate the disparity in the receive quality between the turnstile and QFH antennas upon reception from a NOAA-18 weather satellite. It can be seen that the turnstile's downlink strength was weaker than the QFH which maintained a reception quality of about -35 dB throughout most of the pass. This comparison, however, is an ongoing process, as neither antenna is equipped with a LNA or band-pass filter.

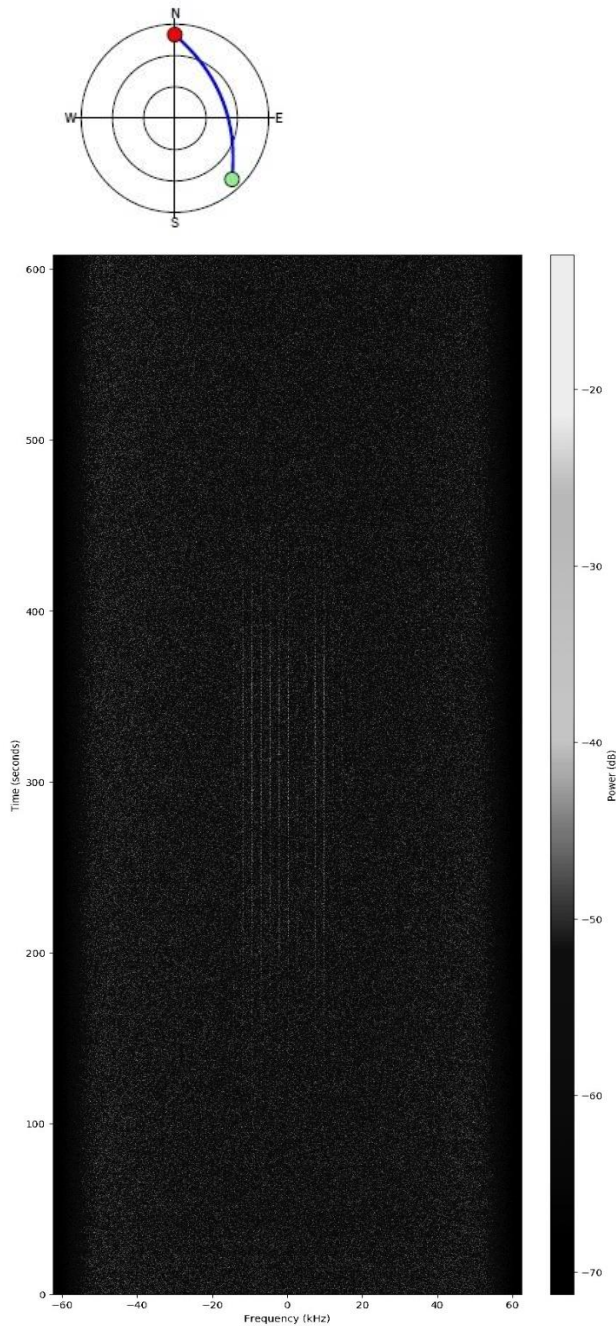


Figure 5a: Crossed-dipole waterfall representation of observation taken during a NOAA-18 pass.

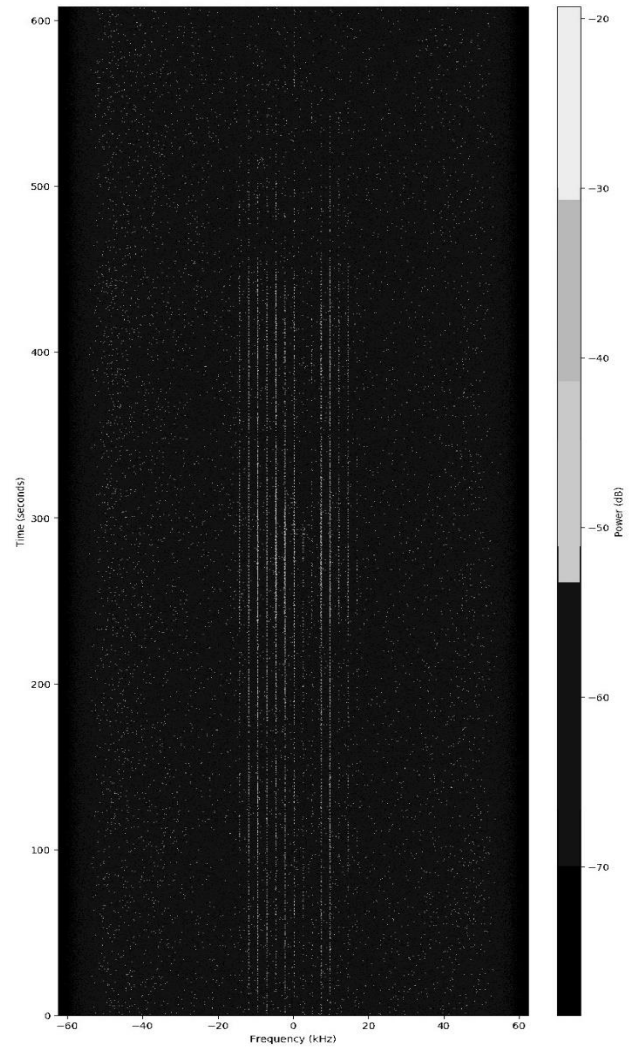


Figure 5b: QFH waterfall representation of observation taken during a NOAA-18 pass.

Conclusion

This study provides a comprehensive analysis of the ease of construction and preliminary performance of the omnidirectional VHF crossed-dipole turnstile antenna and QFH antenna. To provide a standardized analysis we maintained conditions and operating environment. Difficulties during construction were experienced during both antenna builds; an iterative approach will be taken to solve these issues to improve constructability. The initial data suggests that, through VNA plots and waterfall spectrums, the QFH exhibits better receptivity. It must also be noted that this study is ongoing and that any substantial claim on the performance of either of the antennas is dependent on the completion of a satisfactory number of test observations.

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- [2] Adam. *DIY 137 MHz APT Weather Satellite Antenna – Or, Do We Need a Circular Polarization?*
DIY 137 MHz APT Weather satellite antenna – Or, do we need a circular polarization?
- [3] Finell, David P. *Build a 2-Meter Quadrifilar Helix Antenna*. *QST*, May 2018. Accessed 9 July 2019.

A Year with the AMSAT CubeSat Simulator: 12 Months in the Classroom and Lab

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Abstract- The AMSAT CubeSat Simulator is a tool for academic education, public demonstrations and engineering education. It can be used in a classroom or training setting to introduce the basics of satellite operations, or it can be used to teach STEM (Science, Technology, Engineering and Mathematics) concepts, or it can be a stepping stone in a project to build and launch an actual CubeSat flight model. This paper details our experiences using the Simulator in the classroom and in the lab in the twelve months since we unveiled a proof-of-concept design at the 2018 AMSAT Space Symposium. Lessons learned and future plans are also discussed, including the development of “Lesson Plan Core Structures.”

I. BACKGROUND AND INTRODUCTION

We revealed our proof-of-concept model of the new AMSAT CubeSat Simulator in a demonstration at the 2018 AMSAT Space Symposium in Huntsville, AL. The CubeSat Simulator Program was officially “launched” at the AMSAT Update Forum at Hamvention 2019 in Xenia, OH. The new Simulator model provides a functionality similar to the original ARRL ETP CubeSat Simulator built and described in 2009 by Mark Spencer, WA8SME <http://www.arrl.org/files/file/ETP/CubeSat/CubeSat-Pt1-SepOct09.pdf>. We published a series of articles in the AMSAT Journal beginning with the November/December 2018 issue and continuing to the present (<http://cubesatsim.org/papers/>). Each of these articles present a different feature of the Simulator and its accompanying multi-faceted program. The goals and requirements of the CubeSat Simulator are well documented in our earlier articles. This project is fully open source, with all plans, designs, and code necessary to build a Simulator available on Github, our Wiki and Thingiverse.com as directed. Links to all of these sources, along with archives of our articles and other resources are available on the new CubeSatSim website <http://cubesatsim.org>.

II. HISTORY OF THE PROJECT

In the Fall of 2017 at the AMSAT Annual Meeting & Space Symposium in Reno, NV, the AMSAT Area Coordinators (now the AMSAT Ambassadors program) expressed a desire and the real need for a low cost, easily portable, working model of a small satellite for the purposes of education and demonstrations. Immediately, the newly elected AMSAT president, Joe Spier, K6WAO, commissioned a feasibility study for a CubeSat Simulator model to serve these exact purposes and to deliver a concept in one year hence.

Over the Spring and Summer of 2018 at the NASA Goddard Space Flight Center in Greenbelt, MD, three student interns accepted the challenge to “recharge” Mark Spencer’s original Simulator design. University students Nico Lagendyk, Quest Threat and Onyeo Ike-Amaechi succeeded in concluding that the original sheet aluminum structure was not the way to go forward. Nor were the discrete circuits, the stacked board electrical connection scheme and software from the MS Windows XP era of the original CubeSat Simulator. That fall, we earmarked two main challenges to resolve. We pursued a new 1U form factor mechanical frame structure as well as to seek a new processor unit to serve in our Command and Data Handling (C&DH) / Internal Housekeeping Unit (IHU).

The former solution was a slam dunk in selecting a new frame, one formed on a 3D printer using the common STL (STereoLithography) file format. Who today in STEM education does not have a 3D printer within reach? We developed a fine working frame (educational unto itself) with an acceptable robustness for the time being. The link to the free .STL files on Thingiverse is available on our <http://cubesatsim.org> site.

The latter solution, selecting a C&DH processor, came down to a trade study between a modern microcontroller (like those widely used industry, in ham radio projects and, most importantly, in the AMSAT Fox series of CubeSat IHUs) and a small single board computer (like those used in high school academia, ham radio projects and the rapidly growing Maker movement). The processing power of several microcontroller types is considered sufficient for CubeSat flight tasks. The low power requirements of these types make them preferred. In fact, we feel all 1U CubeSat flight unit developers ought to standardize on a microcontroller as its main processor for these reasons (and for radiation considerations in short duration LEO missions that we won’t go into right now). The largest single disqualifier for using a single board computer (SBC) is exposed while performing a simple spacecraft power budget analysis. Generally, the SBC electrical current requirements are shown to be excessive when one considers the demands that would be placed on the Electrical Power Subsystem (EPS) with the power requirements of the other spacecraft subsystems taken into account. For example, the surface area that would be required of the body-mounted solar panels would become too large to be accommodated by a 1U structure.

The Raspberry Pi computer (<https://www.raspberrypi.org/>) is one of the most popular SBCs used in the halls of education today. Consequently, with every release of a new updated version, the “RPI” power requirements have crept upward. Fortunately, the Raspberry Pi Foundation continues to support the humble “low footprint, low power” model they call the Raspberry Pi Zero line of products. In fact, when the Foundation added the WiFi capability, denoted with the W in the Raspberry Pi Zero W name, we had to take a much closer look at this line. The electrical current requirements of the RPi Zero W are marginally compatible with our Simulator EPS. The “flight” battery is charged through the solar panels—and demonstrated as such—when illuminated by the “sun” (a halogen work lamp). Figure 1 shows this arrangement.



Figure 1. AMSAT CubeSat Simulator with Halogen Work Lamp and Turntable.

The stock Raspbian OS runs reasonably well on the Raspberry Pi Zero W, and even better when using the Secure Shell (SSH) interface and *not* a Graphical User Interface (GUI). Coupled with these facts, plus the educational aspects and its versatility, we chose the Zero W in our trade study results for the CubeSat Simulator C&DH processor, even though we do not recommend using an SBC today in a flight model. This is our sole departure from striving toward the space flight hardware design analogy.

We discovered the UHF transceiver board, of all places, across the table at our own AMSAT Booth at Hamvention 2018. Jonathan Brandenburg, KF5IDY, an AMSAT member and leader of the Raspberry Pi User Group in the Dallas, TX area, demonstrated an RPi-compatible transceiver board of his own design at the same time we were searching for such a unit. Indeed, it was a match made in ... Hamvention!

Over the Fall 2018 semester at Villanova University in Philadelphia, PA the AMSAT Custom Solar Power Board, the MoPower UPS V2, the INA219 add-on board sections came together. This development completed the four-board stack design, as shown in Figure 2.

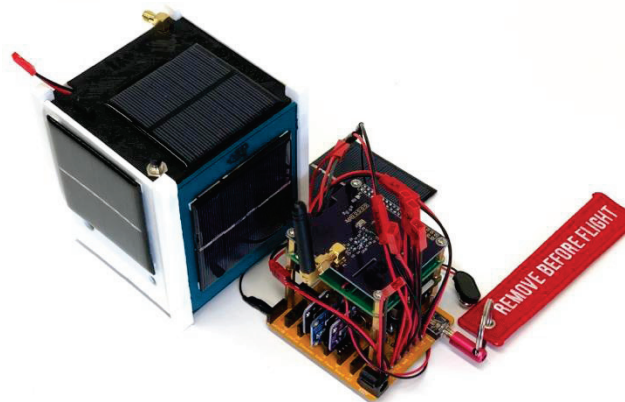


Figure 2. Simulator Four-Board Stack with 3D Printed Frame.

The Spring of 2019 saw tweaks in the overall design of the CubeSat Simulator prototype model and much of the development of the education program to date, plus forming our outstanding team of Beta

Builders and Beta Testers. Four CubeSat Simulator loaner units were built at Villanova, three of them by freshman electrical and computer engineering students in the ECE-1205 Freshman ECE Projects course. These units are shown in Figure 3. We have been shipping these four loaner units across the country. The feedback on their use in the classroom, at events, and in the lab is priceless.

However, with engineers at the helm of this design and early production effort, we could not leave “well enough” alone. We are finding ways to drop the cost of parts, improve performance and increase functionality, as described in our other companion AMSAT 50th Anniversary Symposium paper, “Updates to the AMSAT CubeSat Simulator: Fox Emulation Mode and Raspberry Pi Ground Station.” Don’t miss it.

III. EXPERIENCES IN THE CLASSROOM

This section details the experience to date of the Simulator in the classroom, both at the high school and university levels.

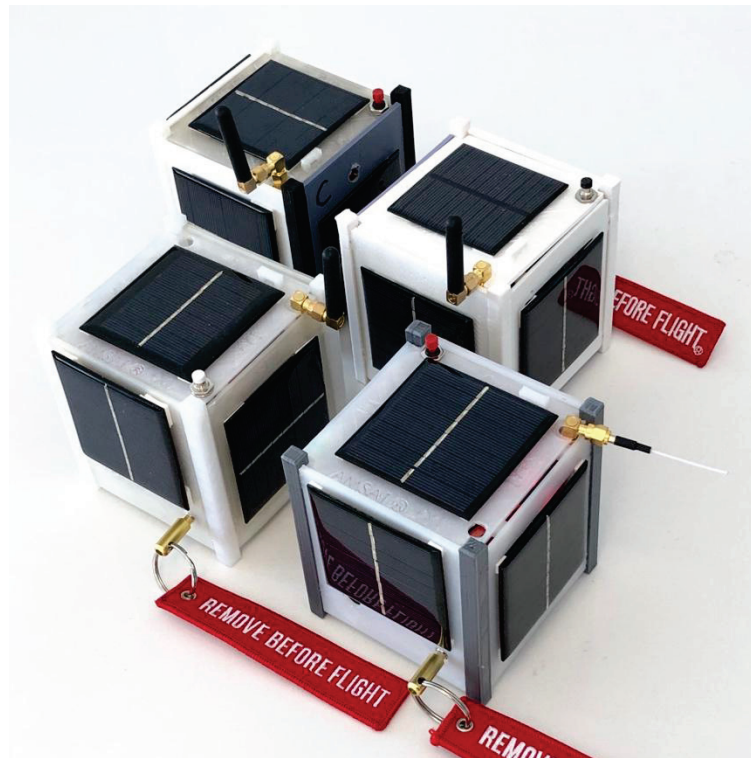


Figure 3. The First Four AMSAT CubeSat Simulator Loaner Units, Available for Classrooms and Events.

A. High School Classrooms

We already have experience with the Simulator in classrooms. At the Fryeburg Academy in Fryeburg, Maine, Warren Ziegler, K2ORS, brought one into his high school classroom. Warren is a beta builder who also has plans to develop a real CubeSat in the future. His students built a Simulator while having the loaner Simulator in the classroom to examine and run tests on.

At Bishop Denis J. O'Connell High School in Arlington, VA, teacher Melissa Pore, KM4CZN, who is also active in the ARISS program, has also used a loaner Simulator with her DJO Engineering Club students. Alan KU2Y enjoyed video calling with her students during their setup and ran tests on the Simulator. After successfully setting it up and learning how it worked, her students demonstrated it at the Innovations in Flight - Family Day and Outdoor Aviation Display at the Udvar-Hazy Smithsonian National Air and Space Museum. Pat N8PK has also provided support to Melissa for her classroom activities. You will likely hear more about what her students have done and some of the great ideas they have for future activities.

At the Grace Brethren High School in Simi Valley, CA, Eric Tapper runs a High School STEM program. He has had his students building a Simulator and learning about satellites and Amateur Radio.

David White, WD6DRI, is involved with the Mt. Carmel Amateur Radio Club, W6SUN, at the Mt. Carmel High School in San Diego, CA. He built a Simulator and plans to demo it and study it at club meetings in the future.

B. University Classrooms

In terms of university classrooms, the Simulator has been used by Villanova University freshmen and seniors and University of Tennessee at Knoxville seniors. At Villanova under Alan, freshmen worked on a seven-week CubeSat Mini Project that involved learning about satellites, building tape measure Yagi-Uda antennas, listening to satellite signals, and dividing up into sub-teams to build six CubeSat Simulators. Three of those became AMSAT Simulator loaner models. One senior design team in Electrical Engineering is working on designing a new Electrical Power Subsystem (EPS) for the Simulator.

Gould Smith, WA4SXM, the AMSAT author of the excellent "Getting Started With Amateur Radio Satellites" publication (the best introduction available today, in our opinion), had his senior design students form teams to analyze the different subsystems and propose and build enhancements to the Simulator. Their distinctions were the Battery Control Unit, Communications Stack (Receiver Team, Transmitter Team, Ground Station Team), Main Controller, and Power Control Unit. One notable design they came up with was an RTL-SDR receiver with DTMF tone detection to turn the telemetry beacon on and off. Gould provided this feedback:

"One of the guys told me he knew nothing about any of this [satellite functions or operations] when he signed on to the project. He is now going to explore satellite design in his graduate studies. We had a number of people get their Amateur Radio license. They all enjoyed working on a practical project and learning new things."

At the University of Texas at El Paso in the Department of Electrical & Computer Engineering, Dr Chris Roberts, KC8GOQ, has built an AMSAT CubeSat Simulator with his students.

These initial experiences show the value of a satellite in the classroom. Also, the low cost and ease of building one opens up a CubeSat and a radio experience to a wider audience.

IV. EXPERIENCES AT EVENTS AND IN THE LAB

The CubeSat Simulator has been to a number of notable educational events, ham radio events and academic & space flight institutions. The feedback from these events has been positive so far.

The K4AMG Memorial Amateur Radio Club used the CubeSat Simulator at NASA Day at the Slover Library in Norfolk, VA, and at the Virginia Beach Hamfest & Convention where they ran a Youth Forum and a Youth Lounge. Thanks to Richard Siff, W4BUE, and Duane Ettwein, KJ4YKG, for taking the CubeSat Simulator to these highly visible events.

The Simulator was shown at the Moon Day event at the Frontiers of Flight in Dallas by Tom Schuessler, N5HYP in July and also at a Satellite Field Day event in St Louis in September by Tom Dougherty, N0TJD.

The Simulator has also been demonstrated as part of an ARISS school contact at the Traverse City (Michigan) Public Library, a two-way radio contact with an astronaut on the International Space Station. Joe Erlewein, N8CN, of the Cherryland Amateur Radio Club showed it off and has since become a beta builder to make his own.

Alan was invited by Rick Lawn, W2JAZ, of the South Jersey Radio Association, to give a presentation on the CubeSat Simulator. Alan received lots of good feedback from that presentation.

Over the summer at NASA Goddard, Pat served as chief consultant to two different student intern small groups who each built one CubeSat Simulator independently in addition to covering their space flight project tasks at hand. Such a mammoth undertaking in such a short time indeed! The students did not completely finish assembling the units, so either N8PK will enjoy another small winter project of his own, or he will “farm out the joy” to one of the readers of this paper!

Simulators have also been taken to a Maker/Robotics STEM education event called Robotstock in Philadelphia, PA, at a table jointly run by AMSAT and the Villanova University CubeSat Club. The positive experiences from this event were described in the AMSAT Journal.

V. LESSONS LEARNED FROM CLASSROOM, EVENT, AND LAB USE

The results so far are encouraging. The teachers who have used the Simulator in the classroom report that the students are excited and interested to work with it. Basic principles of solar power and radio have been discussed and investigated. In addition, each classroom has decided to build one of their own. So, borrowing a Simulator definitely “whets the appetite” to keep a satellite in the classroom.

One issue at the Dayton Hamvention and at various hamfest events has been identified. In the situation where the Simulator needs to be on show for hours at a time, the current lack of extended battery life is a problem. If more than one Simulator were available, such as at the Hamvention or at the Robotics/STEM events, it worked okay by switching between them, with the one momentarily out of sight being placed “on charge.” In the future, perhaps a second 3D printed frame, possibly with a CubeSat Simulator Lite, is a way to provide this. Placing two internal “flight” batteries in parallel has also been tested and seems to work a bit longer. Additional options are open for the student.

At a public event, the brightness and heat of the 250 W halogen lamp is also not ideal. Perhaps one idea would be to use a lower power and temperature lamp for these events.

The Simulators have managed the wear-and-tear of shipping to date. The large, internally-foamed hard-shell cases protect the many contents very well; there have been no reports of shipment damage. One CubeSat Simulator on a table did fall on the floor, which required some minor repairs. One other was over heated by the “sun” lamp and yet another was left in its shipping container in a car on a hot summer day, which, in both cases warped the 3D printed frame. One possibility for the future is to develop a more robust mechanical frame for the loaner models. The other approach is just to assume that the frames will wear out and need to be replaced during the course of a year. Having the loaner units look like 3D printed structures as they are is a good thing, we think, as it can inspire others to print their own frames. Every one ought to have at least one of these beautiful empty frames on display on their desk for showing the 1U life size, and, of course, for any bragging rights you can muster about your own CubeSat or CubeSat Simulator endeavors!

There are some scheduling and logistics work involved in shipping four simulators around. With testing and minor repairs between events sometimes required, these tasks can add up. Since we plan to produce more loaner Simulators in the next year, this could eventually be a challenge with which we will need additional support. One solution would be to have a student intern be the manager of the program who could dedicate a few hours of work to ensure that coordinating happens in a timely manner and that the latest updates to a status list is readily available.

So, the Simulator, as a Project (i.e., building, testing, developing) and a Program (i.e., education, public demos, distributing), is not without its appeal for many reasons, but has its growing pains as well. We will continue to develop and meet these challenges as long as community desire and support continues to flow so nicely.

VI. LESSON PLAN CORE STRUCTURES

We need Lesson Plans, especially for high school teachers. Teachers use them for guiding and instructing their students in the classroom day to day. The teachers largely write their own plans.

We suspect that the professional instructor, however well respected, might lack some of the engineering insight needed to complete a given lesson plan depending on the technical subject at hand, such as any of the myriad of Amateur Radio topics and, certainly, satellite technology de-mystification. So, who are we engineers and technical experts to judge? We cannot write a lesson plan for a teacher. A teacher has the in-depth knowledge of school district curriculum requirements and state education standards. We would otherwise be presumptuous. But can we reasonably provide the teacher with a *core structure* that will facilitate them in their writing task? We plan to try! And we will do.

We will populate a section of our CubeSatSim.org Wiki with a series of what we will call “Lesson Plan Core Structures.” These documents will strive to bridge the gap between professional educators and professional engineers and technology & subject matter experts (SMEs). These sketches are meant to provide a level of technical content, perspective and structure that serves a teacher in his or her own lesson plan development.

Here are the first Lesson Plan Core Structures that we are posting, with updates as needed:

1. “The Voltmeter: How Does It Work and Why Is It Important?”
2. “The Solar Cell & Solar Panel: How Does It Work and Why Is It Important?”
3. “Spacecraft Body Geometry (+X, +Y, +Z): What Is It and Why Is It Important?”
4. “Housekeeping Telemetry: How Does It Work and Why Is It Important?”
5. “The Ground Station: How Does It Work and Why Is It Important?”

We seek feedback from teachers to improve our attempts at writing these structures. We are also looking for technical reviewers. Please email the authors at the addresses given at the top of this paper. Ultimately, we would like to release each structure “signed off” by at least one engineer in the field and at least one well established academic professional. It ought to go without saying that Home Schoolers, Club leaders, Scout masters, Maker organizers and others are welcome to participate as well!

VII. CONCLUSION

We believe it has been a very successful inaugural year for the AMSAT CubeSat Simulator program. We have moved from a proof-of-concept prototype to having four AMSAT Simulator loaners analyzed and demonstrated in classrooms, laboratories, events and forums of all kinds. We have open online documents that allow many beta builders to replicate the Simulator without direct interaction with us needed, although available. We are trying to make inroads to schools to flourish as a result of our Lesson Plan Core Structures.

Looking ahead, we have also developed many technical improvements and enhancements, which we discuss today in our other paper. Please refer to “Updates to the AMSAT CubeSat Simulator: Fox Emulation Mode and Raspberry Pi Ground Station” elsewhere in these AMSAT Proceedings.

VIII. ACKNOWLEDGEMENTS

The Authors would like to thank Jonathan Brandenburg, KF5IDY for his help and assistance. His timely technical support on the Brandenburg Tech Digital Transceiver for the Raspberry Pi Board has been invaluable. Thanks to Mark Spencer for his aforementioned trailblazing work, to NASA summer intern student Nico Lagendyk at UMD-College Park, and to USNA’s Bob Bruninga, WB4APR, for ideas and inspiration from his undergrad “LabSat” developments.

Thanks to the Beta Builders and Beta Users, and especially Villanova University Spring 2019 ECE-1205 Freshman Projects class.

We would also like to acknowledge all the open source hardware and software that is a part of the AMSAT CubeSat Simulator.

Finally, we would like to acknowledge the support of the AMSAT Board of Directors and AMSAT President Joe Spier, K6WAO, for their support and encouragement of this project.

Updates to the AMSAT CubeSat Simulator: Fox Emulation Mode and Raspberry Pi Ground Station

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Abstract- The AMSAT CubeSat Simulator is a tool for academic education, public demonstrations and engineering education. It can be used in a classroom or training setting to introduce the basics of satellite operations, or it can be used to teach STEM (Science, Technology, Engineering and Mathematics) concepts, or it can be a stepping stone in a project to build and launch an actual CubeSat flight model. This paper details recent design updates to a version which include new AMSAT Fox CubeSat satellite emulation modes, and a new Raspberry Pi Ground Station. Also, some planned future development is revealed, along with how we expect to phase in these developments to the program.

I. INTRODUCTION

The AMSAT CubeSat Simulator is a functional model of a satellite for use in education and demonstrations. A proof-of-concept prototype was shown at the 2018 AMSAT Space Symposium, and the CubeSat Simulator program was officially “launched” at the AMSAT Update Forum at Hamvention 2019 in Dayton, OH. Originally, the authors set out on this new Simulator model to provide a functionality similar to the original ARRL ETP CubeSat Simulator built as described in 2009 by Mark Spencer, WA8SME. We published a series of articles in the AMSAT Journal beginning with the November/December 2018 issue and continuing to the present. Each of these articles present a different feature of the Simulator and its accompanying multi-faceted program. The goals and requirements of the CubeSat Simulator are well documented in our earlier articles. At our new CubeSatSim website <http://cubesatsim.org> where we have open source links to the Wiki instructions, a repository of our papers about the Simulator, and to the code on Github. The CubeSat Simulator is shown in Figure 1.

While the main design of the CubeSat Simulator is essentially unchanged since the launch of the program, there are updates in the works. The top two developments are a new Transmitter/Filter (TF) Board and a Raspberry Pi Ground Station, each of which are described in the following sections.

II. NEW TRANSMITTER/FILTER BOARD

Our original model used the Raspberry Pi Digital Transceiver Board, a custom printed circuit board designed by Jonathan Brandenburg, KF5IDY, of Brandenburg Tech. We used Jonathan’s board as it

was available in May 2018 when the new Simulator was under development. An attractive feature of his board was its support for a number of digital modes. Also of note, at the same time, the 1200 bps AFSK AX.25 telemetry mode in the 70cm Amateur Radio band was available as sample code in the DigitalTxRxRPi Github code library, and so the choice presented itself to develop the AMSAT CubeSat Simulator code around it. This combination performed well.

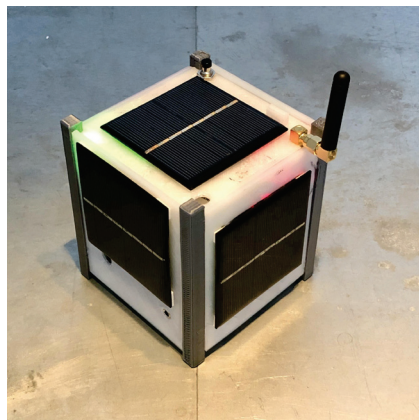


Figure 1. The AMSAT CubeSat Simulator

Nonetheless, two factors led the desire to develop an alternate transmitter board. One was cost, while the other was extensibility. The Digital Transceiver Board is the single biggest cost item in the Simulator. Our desire to reduce the overall build cost of the Simulator nudged us to examine it carefully. In terms of extensibility, we always had plans to support additional modulation schemes so that we could emulate other Amateur Radio satellites. For example, we had partial success in adding CW encoding, but we ran into difficulties emulating the 200 bps FSK (Frequency Shift Keying) modulation used by the AMSAT Fox CubeSats. We also were not able to emulate the 1200 bps BPSK (Binary Phase Shift Keying) modulation to be used by Fox-1E (RadFxSat-2) and the University of Washington's HuskySat-1 3U CubeSat which is flying an AMSAT radio. The difficulty is in programming the AX5043 registers and the lack of documentation available. Also, a core design principle of the Simulator is to use software wherever possible, so relying on hardware for modulation went against that principle.

The new Transmitter/Filter Board uses an all-software approach to modulation. It is based around the rpitx library for the Raspberry Pi by Evariste Courjaud, F5OEO <https://github.com/F5OEO/rpitx>. It uses the Raspberry Pi GPIO clock pin to generate RF signals. This approach is sometimes described as a 1-bit modulator, since the generating waveform is a digital square wave. But when an RF square wave is produced, the resulting fundamental frequency is accompanied by many harmonics and spurs at significant levels. So in order to use this approach, we designed a simple Band Pass Filter plugin board that attenuates most of the spurs and harmonics, down to substantially lower levels.

We use rpitx in the 70cm ham radio band, centered around 434.900 MHz. We chose this frequency because it is close to the 70cm satellite allocation (435 - 440 MHz) but inside the unlicensed ISM band (432 - 435 MHz). We use a simple Band Pass Filter available on the Internet that is centered about 433 MHz with a bandwidth of 2 MHz and a suppression of 30 dB. The left side of Figure 2 shows the spectrum before filtering using a Tektronix 492P Programmable Spectrum Analyzer. A big thank you to Dr Robert Caverly, WB4PWZ, for the use of test equipment in his Microwaves Lab at Villanova

University for these test results. The fundamental is the highest peak, one division from the left side. Each division is 100 MHz, so the strong first harmonic can be seen just over four divisions to the right, and an almost equally strong third harmonic on the right side of the display. In addition, there are many spurs in the 300 MHz either side of the fundamental. This signal quality is clearly not suitable for the Amateur Radio bands in *any* country.

The right side of Figure 2 shows the same signal after being filtered by a \$10 Band Pass Filter. The spurs are gone, and the first and second harmonics are now down 30 dB from the fundamental. The fundamental is about 3 dB down from the unfiltered signal, giving about -30 dBm or 1 μ W of power. This level of filtering is not quite sufficient, but the extremely low power means that this signal is limited to a small room, so the likelihood of interference is very low. In the future, a better BPF design could reduce the harmonics below the typical 40 dB threshold.

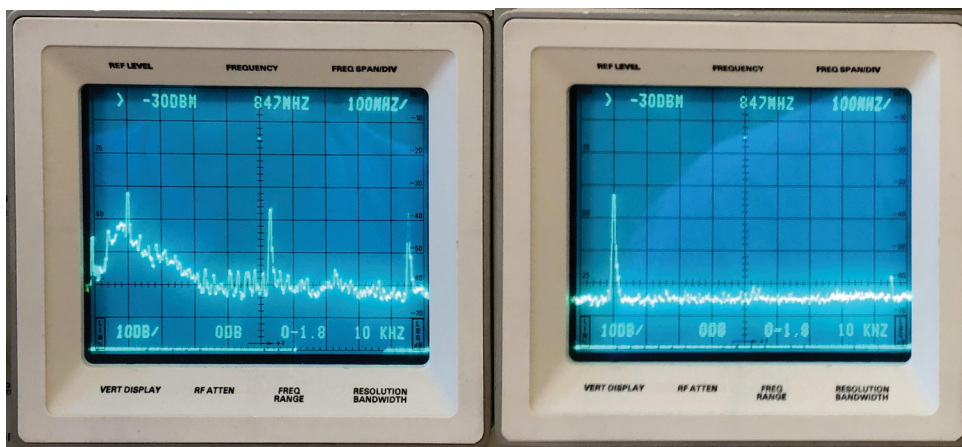


Figure 2. rpitx 434.9 MHz Transmitted Spectrum Before and After Filtering Showing Peaks at Fundamental, First and Second Harmonics.

The completed Transmitter/Filter Board is shown in Figure 3. It is built on a GPIO female header which plugs into a Raspberry Pi. The purchased BPF has SMA female connectors for input and output; we unsolder the input one but leave the output for connecting an antenna. In addition, a 1 k Ω resistor is placed between one of the GPIO pins and ground. The software reads this GPIO pin at initialization, and only activates the transmitter software if the resistor is detected. This should prevent transmission of the unfiltered signal of the left side of Figure 2. An additional GPIO pin is used to drive an LED, with a blue LED used to distinguish it from the previous transmitter board.

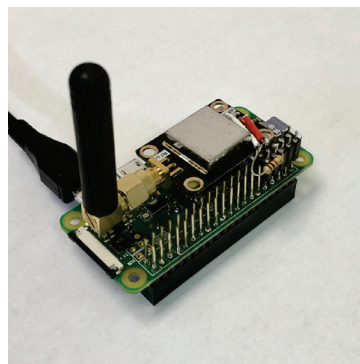


Figure 3. New Transmitter/Filtering Board Prototype on a Raspberry Pi Zero W.

This TFB has a cost of around \$15, which is significantly less than the \$80 of the Digital Transceiver Board. However, the real value is in the extensibility.

The rpitx library includes FM modulation and IQ modulation, which can also utilize the excellent command-line CSDR library (see <https://github.com/simonyiszk/csdrr>) as well for basic DSP and filtering functionality to produce DSB and SSB signals. The FM module just takes an audio WAV file and does Narrowband FM (NFM).

With an appropriate AFSK audio file, generating the 1200 bps AFSK AX.25 telemetry is simple. This allowed us to replicate the current telemetry modulation. Next, we implemented two new modulation schemes: 200 bps FSK and 1200 bps BPSK so we could emulate AMSAT Fox CubeSat satellite telemetry.

III. FOX EMULATION MODE FOR FSK AND BPSK

A goal of the CubeSat Simulator is to provide training and experiences that will carry over to using real Amateur Radio satellites in space. As such, having the Simulator work with the AMSAT FoxTelem software was an important goal (<https://www.amsat.org/foxtelem-software-for-windows-mac-linux/>). FoxTelem, written by Chris Thompson, AC2CZ, is a multi-platform Java application that takes as input a WAV file, audio card, FunCube or RTL-SDR USB Dongle then decodes, plots, archives, and uploads telemetry for the AMSAT Fox-1 series of CubeSats. Currently, amateurs and enthusiasts all over the world use the free FoxTelem software for the Fox-1A (AO-85), Fox-1B (AO-91), Fox-1C (AO-95), and Fox-1D (AO-92) satellites. You can see the live results at <https://amsat.org/tlm> Click on the “latest spacecraft health” link to see the telemetry just as it is displayed in FoxTelem for any of these satellites. In late 2019, it will also be used for the Fox-1E and HuskySat-1 CubeSats after they are launched. With the new Transmitter/Filter Board and new software, the latest version of the FoxTelem software can now be used to decode and display telemetry generated by the CubeSat Simulator.

FoxTelem supports two modulation schemes: 200 bps Frequency Shift Keying (FSK) used by the FM satellites (AO-85, 91, 92, and 95) and soon the 1200 bps Binary Phase Shift Keying (BPSK) of the linear satellites. The details of these telemetry schemes have been well described by the engineering teams in previous AMSAT Space Symposium papers and the AMSAT Journal, so we won't go into detail. However, a big thank you to Chris Thompson, AC2CZ, and Burns Fisher, WB1FJ, for their help in figuring out the 8b10b encoding, framing, and Reed Solomon (RS) Forward Error Correction (FEC). The Simulator code now incorporates open source code written by Chris, Burns, and also Phil Karn, KA9Q (and probably others too)!

The CubeSat Simulator Lite, a lower cost version of the Simulator that only requires a Raspberry Pi and transmits simulated telemetry on the FM radio band, has always used a software only transmitter - the pi_fm_rds application. The discovery of the full featured rpitx Raspberry Pi application, and the CSDR DSP framework allowed us to consider redesigning the Simulator using an all-software transmitter. After we developed this, we discovered this excellent article from AMSAT-SA (AMSAT South Africa) by Anton Janovsky, ZR6AIC, and Cor Rademeyer, ZS6CR, “Software Defined Radio The Concept”. In this presentation and blog post, they create a 2m FM repeater using just an RTL-SDR and a low pass filter <http://zr6aic.blogspot.com/2016/11/creating-2m-fm-repeater-with-raspberry.html>. They also built and sold boards for the design which were available at <http://www.giga.co.za/ocart/>. From the AMSAT-SA page, it seems Anton and others in AMSAT-SA are working on two CubeSats called KletsKous and AfriCUBE that use SDR concepts. Hopefully these CubeSats will be on orbit soon!

A. 200 bps FSK Modulation

For the FSK modulation, we generate a square wave input waveform using differential encoding - we invert the waveform if the bit we are sending is a 0, and leave it unchanged if the bit we are sending is a 1. This signal is then fed into the rpitx application, with the carrier frequency set to 434.9 MHz. Since the Simulator code and rpitx are separate applications running on the Raspberry Pi Zero W, we establish a TCP socket between the applications to pass the data between the applications. The resulting FSK modulated telemetry signal in SDR# is shown in Figure 4.

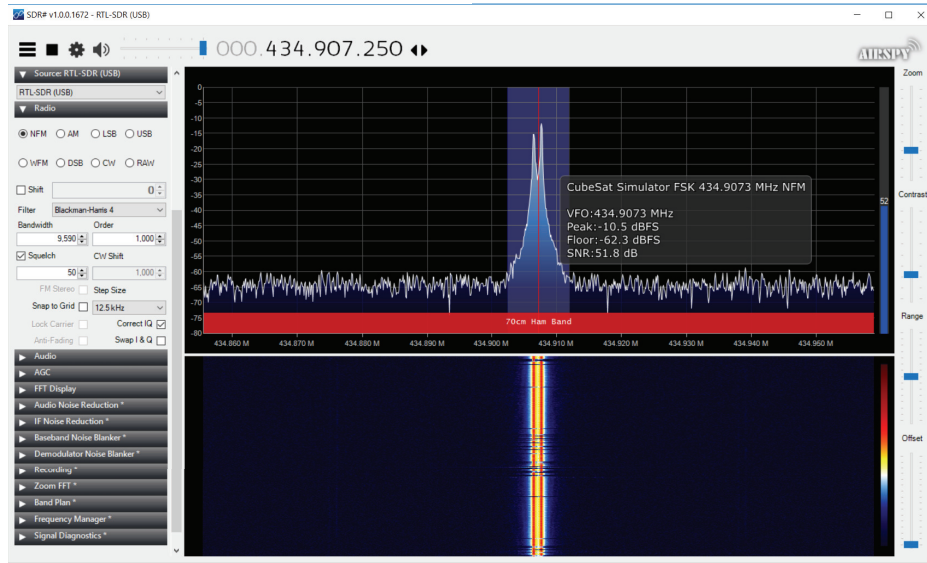


Figure 4. SDR# of FSK from the CubeSat Simulator.

When used with FoxTelem, the result is as shown in Figure 5, which shows the RTL-SDR dongle input to FoxTelem.

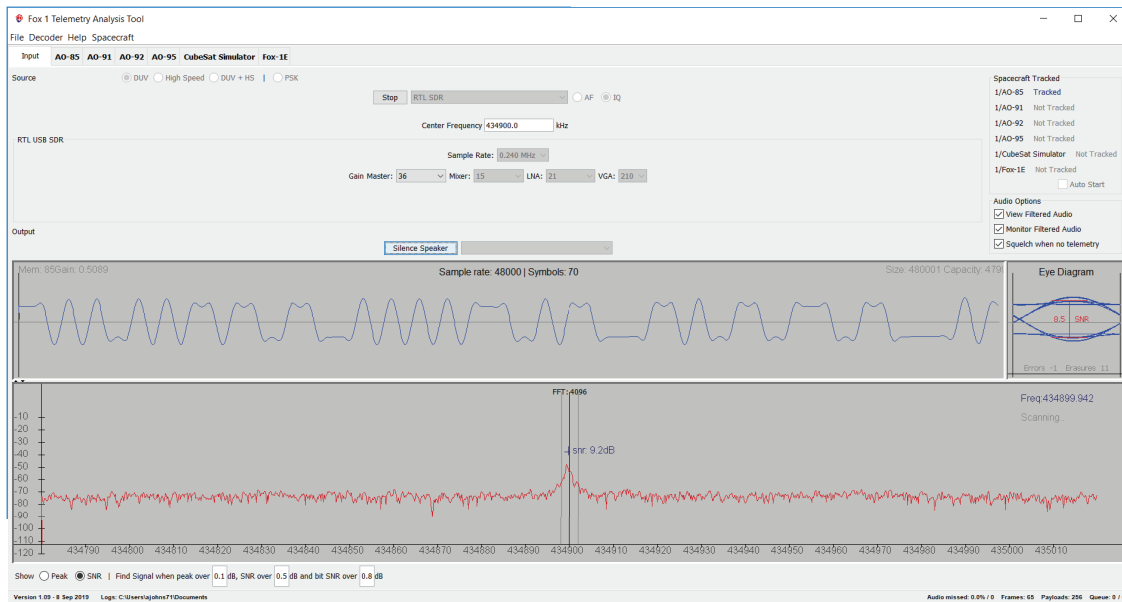


Figure 5. FoxTelem RTL-SDR Input of 200 bps FSK (Data Under Voice DUV format) Telemetry from the CubeSat Simulator

In FoxTelem, graphs of Simulator telemetry can be generated, such as the one in Figure 6 that shows the six solar panel currents and the battery current plotted. This is very similar to the results obtained with the previous Simulator design using the Digital Transceiver Board, SDR# software, VBCable software, AFSK Decoder software, and the telemetry analysis spreadsheet. This is a major simplification! Also, FoxTelem updates graphs in real-time, which is great for displays.

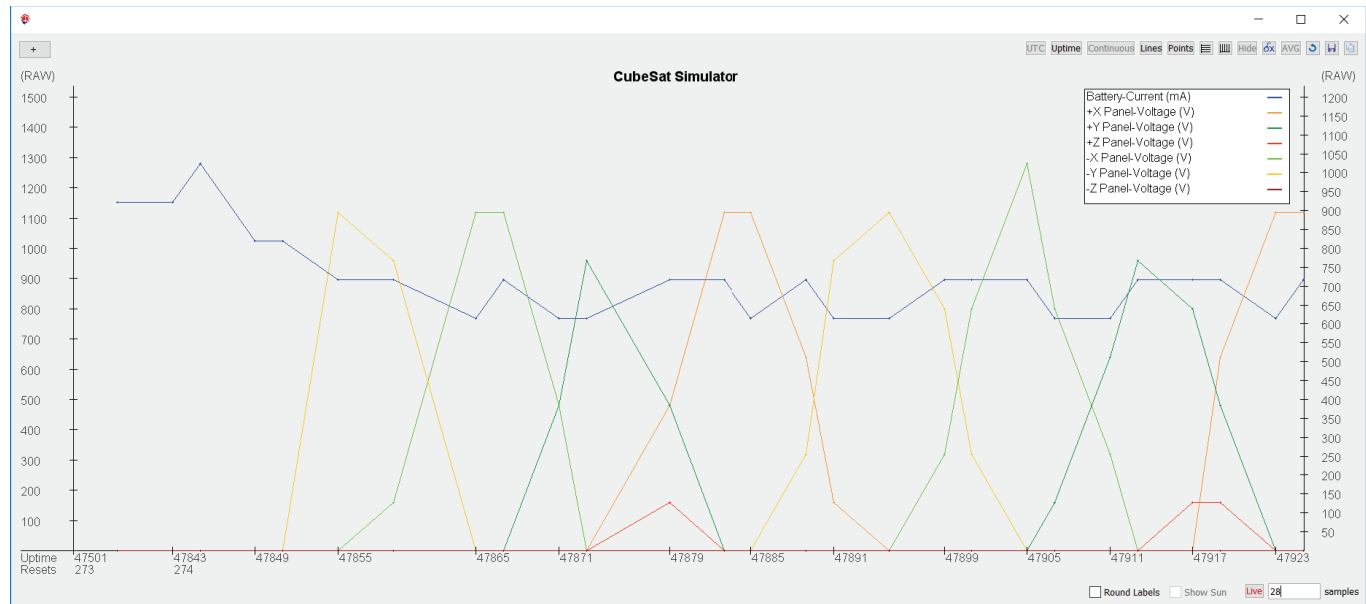


Figure 6. FoxTelem Current Data from the CubeSat Simulator.

B. 1200 bps BPSK Modulation

A similar approach was used for the 1200 bps BPSK modulation. We generate a BPSK waveform by changing the phase of a simple sine wave by 180 degrees, depending on whether a 1 or a 0 is being sent. The resulting waveform is then SSB (Single Side Band) modulated at a carrier frequency of 434.9 MHz and transmitted using the Transmitter/Filter Board. The SDR# reception is shown in Figure 7.

The CubeSat Simulator uses a Fox ID of 7 for FSK and 99 for BPSK (each satellite has a unique id value, and these are chosen to not overlap with any existing or future satellite). This will ensure that Simulator data is never mistaken for real satellite data.

Real satellite data can be uploaded by FoxTelem to AMSAT servers for archiving and review by engineering. In the future, perhaps we could also upload Simulator data to the AMSAT servers. It could be a fun end to a demo or activity to see the data from the classroom or demonstration on the AMSAT page for later viewing or sharing on social media.

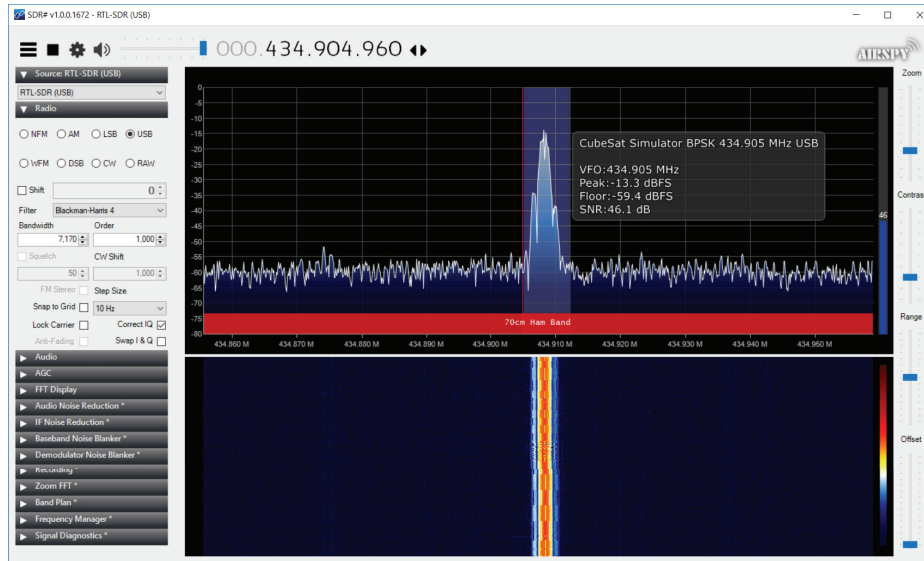


Figure 7. SDR# BPSK of CubeSat Simulator.

By changing the mode from DUV (Data Under Voice, which is FSK) to BPSK, FoxTelem decodes this telemetry as well, as shown in Figure 8.



Figure 8. FoxTelem RTL-SDR input of 1200 bps BPSK (Fox-1E format) telemetry from the CubeSat Simulator.

C. 1200 bps AFSK AX.25 Modulation

The new Transmitter/Filter Board can also be used with the 1200 bps AFSK AX.25 telemetry modulation scheme. We used the `gen_packets` test application in the Dire Wolf (Decoded Information from Radio Emissions for Windows Or Linux Fans) application by John Langner, WB2OSZ, <https://github.com/wb2osz/direwolf> to generate the telemetry signal as a WAV file, then used `rpitx` to modulate the WAV file. The resulting signal is essentially the same as the previous design, although the transmit level is much lower power.

IV. RASPBERRY PI GROUND STATION

The other major update to the design is to add an option for a Raspberry Pi Ground Station. The original design used a PC Ground Station, using an RTL-SDR USB dongle and free software such as SDR#, AFSK 1200 Decoder, etc. The PC Ground Station approach requires administrator privileges and the installation of drivers and software on the PC before it can be used, which can be time consuming and very occasionally fails for what seems like no particular reason. Having a Raspberry Pi with all the drivers and software pre-loaded and installed eliminates this step and these problems. It also supports environments where no PC is available to use as the Ground Station. Raspberry Pi disk images can easily be downloaded, allowing for convenient sharing of configuration.

We described in detail the software needed on the Raspberry Pi in an AMSAT Journal Article. In addition, with the Fox-in-a-Box, described in previous Symposium papers, FoxTelem can be run on a Raspberry Pi to decode the FSK and BPSK Fox-1 mode telemetry. A Raspberry Pi 3B with an inexpensive touch screen is shown in Figure 9.



Figure 9. FoxTelem running on Raspberry Pi Ground Station

A Raspberry Pi can be loaded with all kinds of open source software, making it an ideal tool in education. For example, it can have:

- Gqrx, an SDR receiver application by Alexandru Csete, OZ9AEC, providing functionality similar to SDR# or HDSDR <http://gqrx.dk/>
- OpenWebRX, a Web SDR application by András Retzler, HA7ILM, that provides a web interface to the RTL-SDR. Several users can connect over WiFi using only a browser to tune in and decode signals over a fixed frequency band <https://sdr.hu/openwebrx>
- Libreoffice Calc, a spreadsheet to analyze satellite telemetry
- Dire Wolf, a packet modem TNC for APRS which can also be used to decode the CubeSat Simulator 1200 bps AFSK AX.25 telemetry, and also generate packets as well <https://github.com/wb2osz/direwolf>
- Wxtoimg, for tracking and decoding NOAA weather satellite photos <https://wxtoimgrestored.xyz/>

- SatNOGS, an open network of satellite ground stations, which allows for automated scheduling, display, and decoding of satellite telemetry <https://network.satnogs.org/>
- Gpredict, for tracking satellites also by Alexandru Csete, OZ9AEC <http://gpredict.oz9aec.net/>
- Multimon-ng, a packet decoding utility that can be used to automatically decode the CubeSat Simulator 1200 bps AFSK AX.25 telemetry <https://github.com/EliasOenal/multimon-ng>

For a full discussion of CubeSat Simulator Ground Station options and the use of a Raspberry Pi, see our Part 4 AMSAT Journal article.

V. NEXT STEPS

Our next few steps are anticipated as outlined in the following sections.

A. *Development Phase In of Transmitter/Filter Board*

For the near future, both the old transmitter (Raspberry Pi Digital Transceiver Board) and the new Transmitter/Filter Board will be supported. However, newer emulation modes, such as the Fox-1 emulation mode described in this paper will only be supported on the T/F Board. The same software can be used, as it will auto detect which transmitter board is present.

The T/F Board is being built as a stand alone GPIO plug in board so it can be plugged into the top of the stack where the Transceiver Board used to reside. For those pioneers who have already built a CubeSat Simulator with the original transmitter board, a T/F Board can be built with a stackable GPIO header. Since there is room inside the frame, this stackable T/F Board can be plugged in on top of the Raspberry Pi Zero W in the stack, and still have the Transceiver Board available. The SMA antenna connector may need to be moved manually or a second antenna mounted.

As for the program, we will gradually add the stackable T/F Board to the AMSAT loaner Simulators to add the Fox-1 emulation modes and a Raspberry Pi Ground Station. New builders of Simulators will have a choice. The T/F board is cheaper and easy to build. However, in the future, the Digital Transceiver Board could perhaps be used as a 2-way command and control radio interface with the Simulator.

B. *Battery Management Board Replacement*

A future step planned to reduce the cost of the Simulator is to design a new Battery Management board to replace the MoPower UPS V2 board, which currently costs \$60 and handles battery charging, monitoring, and does automatic and manual shutdown of the Raspberry Pi. Replacing this board with our own battery charging board will further reduce the cost of building the Simulator.

C. *Next Solar Power Printed Circuit Board (PCB)*

In the next redesign of the Solar Power PCB, we will add the Transmitter/Filter functionality to this board, which will reduce the board stack count and further reduce build costs. The newly designed Battery Management Board may also be added to the PCB, reducing the board stack count and cost. A bonus here is that the extra volume might better accommodate an instrument or payload in the 1U frame.

VI. CONCLUSION

The original design for the CubeSat Simulator has proven to be effective in meeting the goals of the CubeSat Simulator program. The design updates described in this paper are enhancements, to provide additional functionality and reduce the build cost.

We also plan to make some additional developments in the future, especially around the battery board. However, we expect most of our future development to be in documents and educational materials for teachers and demonstrators of the AMSAT CubeSat Simulator.

VII. ACKNOWLEDGEMENTS

The Authors would like to thank Jonathan Brandenburg, KF5IDY for his help and assistance. His timely technical support on the Brandenburg Tech Digital Transceiver for the Raspberry Pi Board has been invaluable. Thanks to Mark Spencer for his aforementioned trailblazing work, to NASA summer intern student Nico Lagendyk at UMd-College Park, and to USNA's Bob Bruninga, WB4APR, for ideas and inspiration from his undergrad "LabSat" developments.

Thanks to the Beta Builders and Beta Users, and especially Villanova University Spring 2019 ECE-1205 Freshman Projects class.

We would also like to acknowledge all the open source hardware and software that is a part of the AMSAT CubeSat Simulator.

Finally, we would like to acknowledge the support of the AMSAT Board of Directors and AMSAT President Joe Spier, K6WAO, for their support and encouragement of this project.

DJO and the AMSAT CubeSat Simulator Loaner Kit

Will Rimicci and Elaine Ly

Bishop O’Connell High School, Arlington, VA

Faculty Advisor: Melissa Pore, M.Ed. KM4CZN

Our team is from Bishop O’Connell High School in Arlington, VA. Our first interest in satellites began at St. Thomas More, a school in Arlington, which we all attended. There, we designed, built, and launched a CubeSat named STMSat-1 with a team of 400 students. Now that we are at the high school level, we are considering another CubeSat. Last April, we launched a ThinSat called DJOSpaceToast. We plan on launching another ThinSat in the fall of 2020.

We first learned of the CubeSat Simulator in the spring of 2019, and we received an AMSAT loaner simulator in June during finals week. After speaking with Professor Alan Johnston and practicing with the software, we had learned enough to start teaching other people. We brought the simulator to the Udvar-Hazy Air and Space Museum near Dulles Airport on June 25, 2019, for their Innovation Day. We set up a table and talked with kids, parents, and other adults about what the simulator is and why it is important.

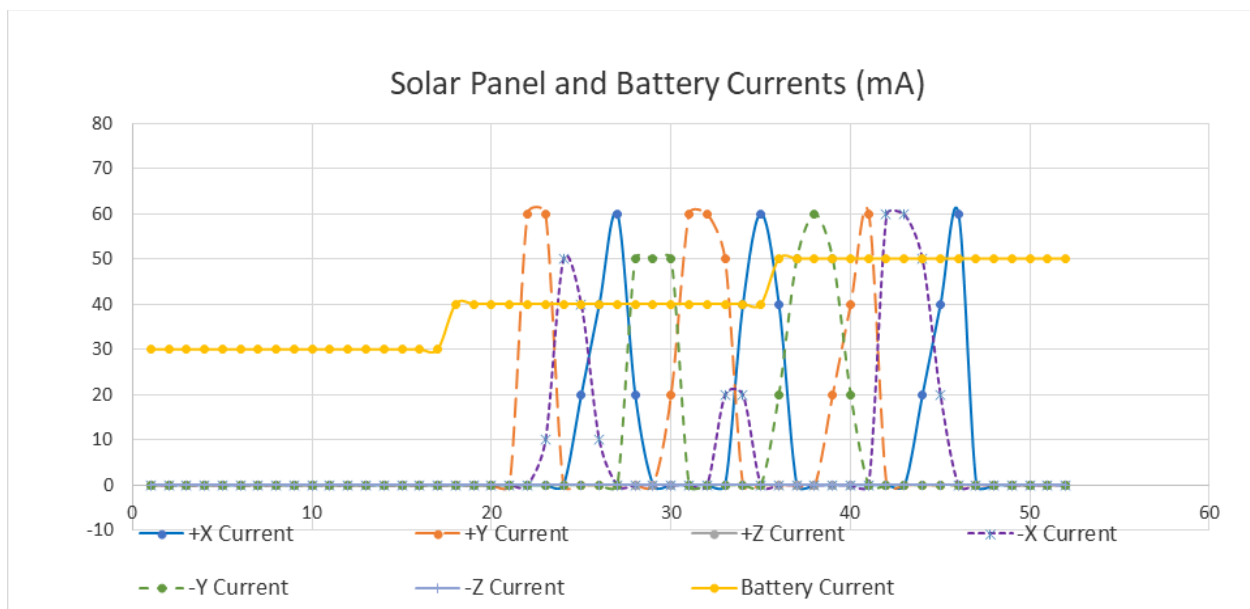
We worked extensively with the SDRSharp software and the simulator. During our data collection, we discovered the CubeSat Simulator was rather difficult to keep intact. The main issue was that the 3D printed latches occasionally broke off, and we had to resort to hot-glue. After noting these observations, we submitted improvement suggestions to one of the inventors, Mr. Pat Kilroy. Consequently, we acquired the simulator with additional modifications. These included zip-ties, an improved LED, and an externalized plug.

Currently, we hope to further our learning experience with the newly modified CubeSat Simulator. We anticipate future demonstrations at our school and at local venues, such as Udvar-

Hazy and College Park. We are excited to work on an added module we are calling the “Simulator of the Simulator,” in which students could access the physical sim with an app as well as simulate the entire process with an animation. Other features would include a catalog of options or accessories to power and operate the simulator, choice of solar panels, orbits, and other common features. The animation of the live simulated model would appear in a window above while the selected variables would appear on graphs below.

We expanded the CubeSat’s teaching potential through these modifications to the simulator; the more we can simplify its use, the better we can teach other students. With the AMSAT CubeSat Simulator program, we hope other high school students will have the opportunity for hands-on experience with a working model. Ultimately, introducing this simulator to children can aid them in their resolution to enter a STEM field as adults.

Thank you for your time.



Solar panel data captured in one run of the CubeSat Simulator

THREE COLLEGE STUDENTS' PERSPECTIVES ON HAM RADIO AND AMATEUR RADIO SATELLITES

Dawson DUCKWORTH (KC3NNB)

Lauren HURLEY (KD2RHC)

Kaixuan Ji (AC3EN)

ABSTRACT

We are three college students at Villanova, PA who recently got our amateur radio licenses. We share our personal stories of how we became interested in ham radio, passed our tests, and became involved in amateur radio satellites. We also share our opinions on what the amateur radio community and AMSAT should do to encourage more new participants such as us.

I. INTRODUCTION

We are three college students attending Villanova University in Villanova, PA who recently got our ham radio licenses and are involved with amateur radio satellites. In this paper, we explain how we learned about amateur radio, what motivated us to get our licenses, and what we like about the hobby. Finally, we give our opinions on what the amateur radio community and AMSAT should do to attract more people our age to ensure the future of the hobby. Each of our perspectives is in a separate section.

II. DAWSON DUCKWORTH'S PERSPECTIVE

I am currently a junior at Villanova University studying Electrical Engineering with a minor in Computer Science. I have been interested and fascinated by science and particularly space my entire life watching shows such as Neil deGrasse Tyson's "Cosmos: A Spacetime Odyssey" and Carl Sagan's "Cosmos: A Personal Voyage". I am not sure what it was that always kept drawing me back to studying space but every time I look up into the sky at night, I always like knowing that we are only a small speck in a possibly infinite universe that is billions of years old and will still be active for billions of years after we are all gone.

On the first day of my Fundamentals of Electrical Engineering Lab, Dr. Alan Johnston, KU2Y, who had just started teaching at Villanova, asked the class if anyone was interested in starting an amateur satellite/ radio club because the school did not have any space-related engineering clubs. I knew this was my chance to do something other than just watching documentaries on TV, so I talked to him after class and later that year, we formed the Villanova CubeSat Club. Since then, we have improved designs on the prototype CubeSat Simulator that Dr. Johnston had made, we attended events such as Hamvention in Dayton, OH, and RobotStock in Oaks, PA. We have grown as a group so much since the beginning of the club last year and with the support from the school, we intend to accomplish some impressive goals this year.

One of the first activities we worked on as a club was to contribute to Satellite Network Operators Ground Station (SatNOGS) with Raspberry Pi's. This was the first time

I had ever heard of amateur radio and I did not really understand what it was used for. I did not know before starting the CubeSat club that you could communicate with people all around the world by bouncing signals off satellites or that everyday people could pick up telemetry from a satellite with only an antenna and an SDR (Software Defined Radio). After some club meetings, we even went outside and try to pick up signals from some of the AMSAT satellites as well as weather satellites and the ISS (International Space Station). By attending these “listening parties,” a lot of interest in amateur radio was built up throughout the club and some members began getting their technicians licenses, including myself. I got my technicians license, along with two other club members, at Hamvention in May of this year. Since then, I have been excited to go to amateur radio and satellite events and talk to people who have so much more experience than me in the field. I am hoping to learn more in the future.

The amateur radio community has a long tradition that is still around today. Over the past year, I have met college students who got their licenses for many different reasons. Having said that, the community needs to advertise to younger people in colleges and even high schools because most people know nothing about the community. If AMSAT were to fund radio clubs in colleges, I am certain that more people would join the community, but it needs to happen sooner than later. I see the amateur radio community growing in the future but AMSAT and other organizations need to advertise across the country for that to happen.

III. LAUREN HURLEY’S PERSPECTIVE

I first learned about amateur radio in my Introduction to Electronics course last year at Villanova. I loved this course because it was offered through the physics department, so we learned how electronic components work on a fundamental level, not just how to use electrical equipment. Later in the semester, our professor Dr. Jeremy Carlo, N2ZLQ, devoted an entire class period to discuss amateur radio. We learned about the history of how radio developed, how radio signals carry information, and how receivers work. At the end of the year, we all had to do a research project on a subject of our choice. I chose amateur radio because I wanted a more comprehensive understanding of radio technology, as well as the history and culture of ham radio. By the time I had finished this project, I realized that I knew most of the material covered on the Technician License exam. I had four weeks off for winter break, so I borrowed an ARRL license manual from the library, reviewed it, and passed my license exam in January of this year.

When I was researching for my project, I checked out several old books from the Villanova library. In this way, I learned how amateur radio used to work before satellite communication and before repeaters. One of the books mentioned the AMSAT satellite OSCAR 7 as new development. I’m interested in satellites because they offer a new possibility for amateur radio. The CubeSat Club spent some time in the spring tracking satellites and trying to make contact, and it was more exciting than I expected. Using repeaters to talk on a handheld almost seems too easy. Satellite communication adds a new thrill to making contacts: one only has a limited time while the satellite is passing overhead, so time is of the essence. On a linear satellite, if one sees someone else talking on a different frequency, one has to decide whether to “chase” him and switch frequencies or keep calling CQ on the same one. Moreover, satellite communication is accessible even

to people without their licenses. With a little equipment, anyone can track satellites and listen to hams or receive telemetry. Thus, satellites expand the scope of the CubeSat Club, because even non-hams can participate and learn how satellite signals work.

However, with the proliferation of communication technology in the past half-century, radio contact may have lost its appeal. Young people growing up with cell phones won't marvel at making a QSO the way their grandparents did. In my opinion, the way to attract new members would not be to hand them a brand-new handheld and stress how easy it is, but to do the opposite. This new generation loves do-it-yourself projects. Many public libraries have introduced "maker spaces" where patrons can come to build or sew things. Indeed, crafts like sewing and knitting have seen a huge resurgence in recent years. I myself was drawn to knitting because I liked the idea of understanding how to make clothes, and to make them exactly how I liked. To attract new members, AMSAT should stress that ham radio is no different. This hobby offers enormous potential for people to build things themselves and customize what they make. Then, amateur radio will stand out from other communication methods, like texting or phone calls, and seem less like "magic" and more like an art. For instance, our club built Yagi antennas with some wood and tape measures. Everyone was shocked how simple it was. In this era of online shopping, we expect things to come packaged and complete without understanding how they function. So when we do it ourselves, it is a moment of wonder and deeper comprehension.

IV. KAIXUAN JI'S PERSPECTIVE

I am a junior who is currently pursuing my Bachelor of Science degree at Villanova University with a double major in Electrical Engineering and Physics.

I bought a book on amateur radio communication back when I was in middle school. However, I spent all my free time running around on the playground rather than sitting down and reading. Last year, my Electronics professor, Dr. Jeremy Carlo, N2ZLQ, was the president of the Mid-Atlantic Radio Club (MARC). He brought his ham radio equipment to class when we were on the topic of telecommunication and reignited my interest in amateur radio. Later that semester, I found out that my Fundamentals of Electrical Engineering professor, Dr. Alan Johnston, KU2Y, the faculty advisor of the Villanova CubeSat Club, is also a ham. Last summer, three CubeSat Club members including myself went on a field trip to Hamvention to represent the AMSAT CubeSat Simulator of the club at the AMSAT Education table. Before the trip, I spent a week reading the ARRL License Manual to get prepared. As a result, I got my Extra license at Hamvention on the first day!

Amateur radio technology is a great educational tool for Electrical Engineering classes. For example, performing signal processing on a blackboard or in MATLAB (matrix laboratory) is relatively abstract while it is relatively figurative on a transceiver; the audio can make the process come alive. For a decent transceiver, the transmitted or received audio can even be displayed as an FFT (Fast Fourier Transform) on the oscilloscope. Students can learn about multiple digital communication protocols, which will be helpful in some of their upper-level classes.

Amateur radio also can provide emergency communication when internet, phone service, and other conventional communication methods fail during times of crisis. Even when there is no disaster, amateur radio can serve as an emergency communication tool during populated events. Also, after getting his/her license, one can join organizations such as Amateur Radio Emergency Service (ARES) and Radio Amateur Civil Emergency Service (RACES) and contribute to communications in public service for an even broader community.

Satellites play important roles in many science and engineering disciplines. However, it is hard for people to feel the existence of satellites since the satellites are far away from us, serving silently. With the help of organization such as SatNOGS, one can easily set up a satellite ground station by using a Raspberry Pi. It is always fun to play with the ground station! In the meantime, CubeSat Simulator is a great educational tool for people, especially high school students, to learn about satellites and related technologies. More importantly, it is portable and affordable, so it has the potential to enter classrooms all around the world.

Getting people's attention about ham radio and satellite technology and encouraging them to join clubs and organizations is important. However, it is more important to ensure people decide to stay involved so that they can grow and get back to the community. Though there are many resources online about satellites, it is not easy for one to get started: tracking satellites and making satellite contacts can be tricky and time-consuming. Thus, it is important to have volunteers who play the role of "Elmer" and help the newcomers in AMSAT to utilize all the resources that the organization has to offer. If the community continues to grow, building a geostationary amateur radio satellite will no longer be a dream but a reality. I wish AMSAT luck on launching a GEO satellite as soon as possible.

V. CONCLUSION

In conclusion, we all got involved in amateur radio at the start of our college careers and share a passion for learning about the hobby. We were lucky to be exposed to this craft, but unfortunately that is not always the case. AMSAT should devote more efforts to community outreach to let more people know about ham radio. Moreover, AMSAT should stress the do-it-yourself aspect of the hobby to attract new members. AMSAT has a lot to offer but needs to make efforts to keep the tradition going. We're excited to see what the future of amateur radio will hold.

A Successful Random ARISS Contact with \$120 Station Setup

Daniel Ernandes, KK4HBI

Abstract

On October 11th of 2012, at approximately 1935 EDT, I contacted the International Space Station using a hand-held IC-V80 and a J-pole antenna. This contact was attempted on several passes before success, using a smartphone app that tracks passes of various satellites. The contact began with no squelch to increase the chances of hearing a reply, and the beginning of the contact was quite static filled. Most of the contact used the lowest level of squelch at full quieting and conversation was “armchair copy” for the full pass while above a 15 degree elevation. The total cost of the transceiver is approximately \$100, with the remaining \$20 consisting of the coax, connectors, and copper piping for the antenna. This demonstrates the feasibility of making a random ARISS contact using a very modest ground station.

Introduction

While the possibility of contacting the International Space Station via amateur radio is well known and is even quite popular, few have done it without an expensive home station or know it is possible at all. Not only is it possible, but one does not even need an expensive setup. With only a modest beginner’s transceiver and antenna along with proper timing, anyone could have a chance to contact the ISS.

Station Setup

The station used in this contact is a very basic setup. Its only parts were an ICOM IC-V80, a J-pole antenna constructed from copper plumbing tubing and clamps, and the coaxial cable and connectors to bring the two together. The transceiver ran on four AA batteries and had 5 watts of output power. It cost approximately 100 dollars and possessed only the most basic of functions such as several levels of manual squelch, a CTCSS code input, limited frequency memory, and half-duplex transmission/receiving function.

The antenna consists of a few lengths and junctions of copper plumbing pipe with a SO-239 connector. The antenna is 62.25” long, however the radiating element is 55.5” long with a tuning stub 17.5” long. The antenna was tuned by adjusting the feed locations on the stub and the main element, and then holding it in place with a pipe clamp. The pipes and coax connectors were then soldered in place using a propane torch, and was connected to the transceiver using approximately three feet of 50 Ohm coax cable with a PL-259 connector on one end for the antenna, and a BNC connector for the transceiver.

Contact Setup

The contact was attempted several times over the course of a few weeks using a smartphone app that tracked the locations, azimuth, and duration of various satellites and their passes overhead. This list included the International Space Station as well as several other Amateur Radio repeater satellites. During each of these attempts, I tracked the station across the sky by either the app, or by eye if it was in the sun, and kept the horizontal J-pole parallel to the ISS as best as I could to ensure maximum signal strength. As an example of the low-cost solutions I was employing, I have placed my station where it was at the time of the contact to take this photo.



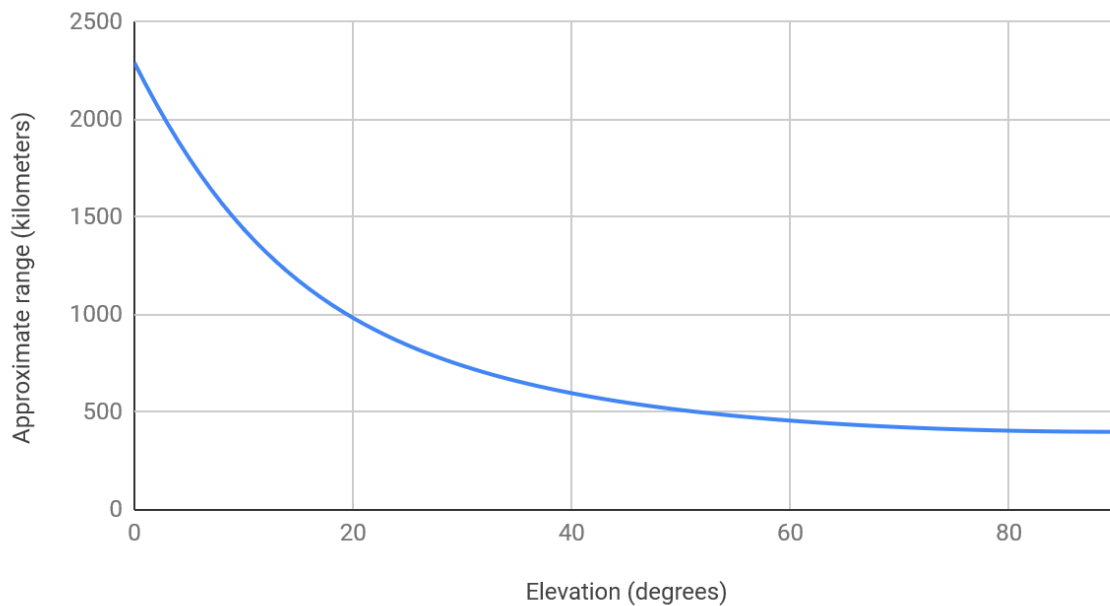
All of these contacts were attempted in the afternoon and evening Eastern Time, as that was the only time I could try, however I learned after the fact those times are extremely unlikely to succeed as they clash with the astronaut's schedule. The optimal time would have been at approximately 0700 UTC, which is shortly after they wake and have no work scheduled.

Contact

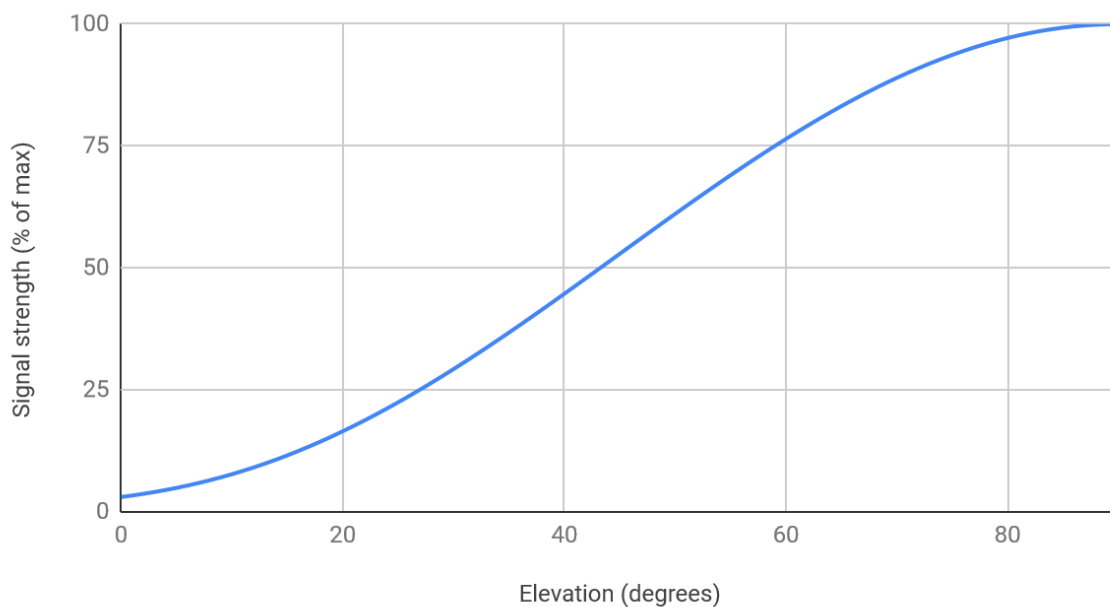
The successful contact was attempted around 1930 Eastern Time, and as I began to call NA1SS, the first few minutes were filled with atmospheric static. Due to a combination of doppler shift, low power, and distance, the signal was extremely weak at a low angle above the horizon, but once the station rose clearly above the horizon, the contact was made.

The graph below illustrates the relationship between the elevation of the station and the range to me. This significant drop off in distance at low elevations explains how the contact was impossible at very low angles but with a rise in a few degrees, the range closed enough for the path loss to be low enough for a stable contact to be made.

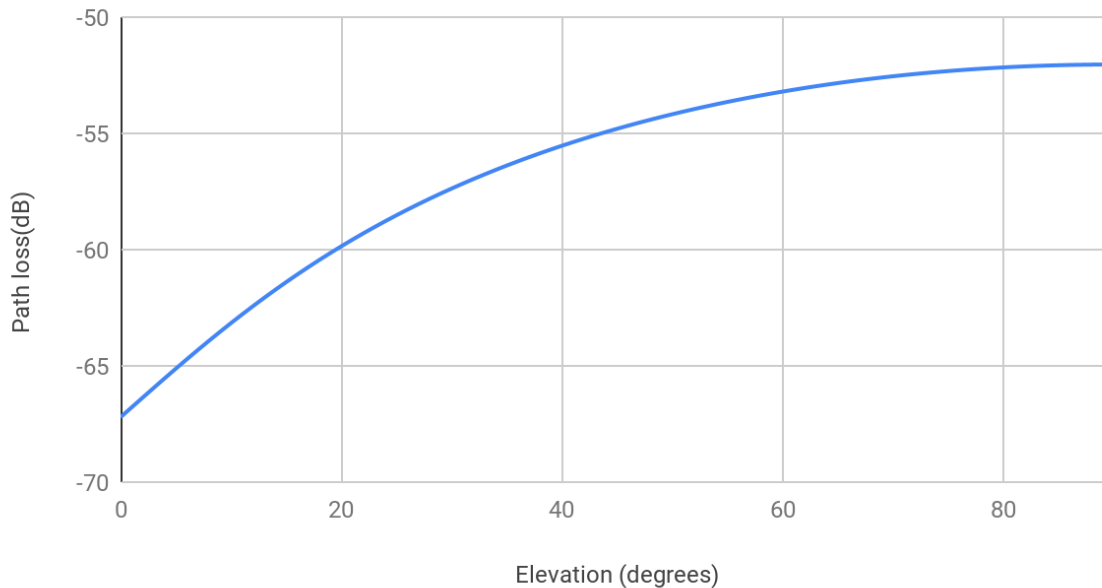
Range



% max signal strength



Path loss



The above two graphs also show the sharp increase in signal strength and the decrease in path loss as the elevation increases. By 10 degrees, the range from 0 degrees had closed by over 900 kilometers, the path loss had dropped by 5 decibels and signal strength had increased by 2.5 times. By 15 degrees above the horizon, compared to 10 degrees the range had closed by another 250 kilometers and the signal had increased another 50% (almost 4 times the strength at 0 degrees).

At this point the signal was approximately 11.6% of full strength and the path loss had dropped by approximately 6 dB from 0 degrees. As the contact progressed there was another 9 dB reduction in free space path loss until 90 degrees, and the range had closed to approximately 400 kilometers.

Beginning at approximately 10 degrees above the horizon, Station Commander Sunita Williams' static-filled voice began speaking back to me. Once above 15 degrees or so I was able to put the lowest level of squelch the IC-V80 had on, and the contact was full quieting until the station proceeded back down below approximately 15 degrees on the other side of the horizon. The pass was almost directly overhead and so I enjoyed an approximately 5 minute long contact at full quieting, with about a minute or two on either side with static.

Conclusion

Many people may not have realized that it is possible to randomly contact the International Space Station at all, let alone with such a low power and simplistic station setup. My experience shows the feasibility of such a contact, and that with proper planning and persistence any operator could have one of their own.

Work FM Satellites with your HT!

*Most hams already have nearly all the equipment to work FM voice satellites.
This guide offers a quick start for successfully making contacts!*

All cited resources are available to you at one Web site:

work-sat.com

If you have 2-meter and 440 capabilities (either “split frequencies” in one HT, or two radios), you can work FM voice satellites! For example, in satellite SO-50’s VHF/UHF (V/U) mode, the **UPLINK** frequency (to SO-50) for FM voice is 145.850MHz. The **DOWNLINK** frequency (from SO-50) is 436.795 MHz.

First, you need to know **WHEN** and **WHERE** the satellites will be passing over your location. There are several commercial computer programs^[1] that will tell you. In the home office, I use **MacDoppler** or **GPredict**. Outside, I’ll use **PocketSat3** or **GoSatWatch** on my Smartphone. On Windows systems, **Nova** and **SatPC32** are marvelous. But there are free-of-charge info sources online, too, at ...

heavens-above.com -or- amsat.org -or- N2YO.com

Log in to these sites, plug in your grid square, and you will have access to accurate satellite pass information.

The one “absolute” for success is to **open up your SQuelch**. We are talking about “weak signals” from hundreds of miles away - so don’t expect the satellites to be strong enough to break squelch like your local repeater does. Sure, it’s a little noisy - but that’s part of the process: That noise is an aid in locating the satellites! When the frequency starts exhibiting **quieting**, that’s a sign that you are **capturing** the satellites’ signals.

Improve your HT’s stock antenna (most are rated at **NEGATIVE 6db** - or worse!). The **Smiley 270A**^[2] is a good performer, and is available in Male SMA, Female SMA, and Male BNC models. But for best success, you need more **GAIN**, so using an **Arrow Satellite Antenna**^[3] or **Elk Log Periodic** is much better. If you prefer to home-brew your antennas^[4], go to the work-sat.com Web site’s **ANTENNAS** page for construction article links: You can get in to the world of high gain operations for as little as \$15!

For SO-50, set up your radio to tune for the **Doppler effect** on the 440 downlink. Start listening **above** the center frequency - you will **acquire** the satellite sooner and clearer. When the downlink gets scratchy or fuzzy, tune down 5KHz at a time, and reception may be clearer. Only transmit when you can **clearly** hear the satellite. Follow the signal down in frequency as the pass continues. Satellites AO-91 and AO-92 birds are a little different, with their **440 uplinks** (which may require minor Doppler adjustment) and **2M downlinks**. See the frequency charts at the end of this document.

If using a whip antenna, don't hold it upright. Held in a vertical position, your transmitted signal is hitting land-based receivers. Most of our satellites are not land-based (grin). You need to tilt your HT's antenna about the same amount as the satellites **ELEVATION**. Get it perpendicular to the orbit's path! You will quickly get the hang of it - and hear the difference. Again, you will have much better results with a modest beam or Yagi antenna.

Ideally, we should be working the FM voice satellites in **full-duplex** mode, where we can simultaneously listen to the downlink as we are transmitting. Although this method is preferred, it is not mandatory: Carefully monitor the downlink, and wait for a break in the conversations to key your mic and announce yourself. You might find it helpful to record your sessions for later review: Even if you do not make a contact during a pass, a recording can help you recognize the callsigns and voices of other operators. Pocket recorders or Smartphone apps are great for this. And if working full-duplex, use an earpiece or headset to monitor the downlink to avoid acoustic feedback.

Knowing your grid square - and having a grid square map - is a quick way of identifying locations of operators you will hear. The **ARRL** and **Icom America** have grid square maps: Icom's is free and available at better ham radio stores^[5].

It just takes a little preparation and planning for working FM voice satellites. Not every pass is workable with an HT - don't go after the sub-10-degree elevation passes as you start "working the birds." Choose your passes wisely: Working higher elevation passes will give you much better results.

When you clearly hear others, listen for a break in the action, key your mic and use the ITU-approved phonetics^[6] to announce your callsign, grid square, and - **optionally** - operation mode:

"KILO SIX LIMA CHARLIE SIERRA, DELTA MIKE ONE THREE, HANDHELD."

Check work-sat.com for the satellites' home pages - to make sure the satellites are in the modes you can work with your setup!

Clint Bradford, K6LCS
k6lcs@ham-sat.info

work-sat.com
(909) 999-SATS (7287)

Updated August 11, 2019

Notes

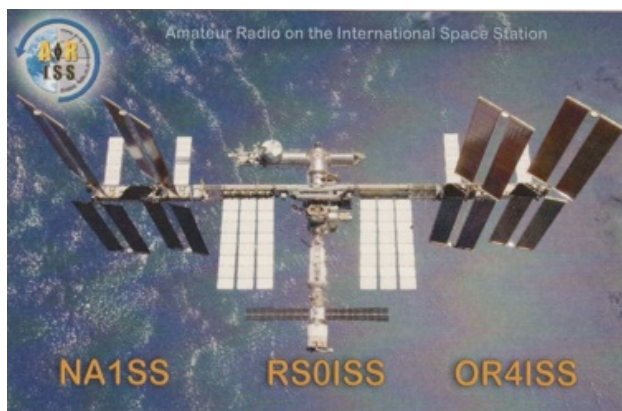
[1] - Links to several satellite pass data programs - as well as free online resources - available on the **TRACKING** page at work-sat.com.

[2] - The Diamond RH-205 is a collapsible 2M BNC antenna. Be careful using it - its mass places a lot of stress on your HT's antenna connector. The Smiley 270A (which out-performs antennas 2X its price!) is available at **Ham Radio Outlet** - hamradio.com - or from **Smiley's Web site** at htantennas.com.

[3] [4] - **Arrow's Model 146/437-10WBP** is a dual-band cross-Yagi design, with a diplexer built into the boom's handle. Links to the Arrow - as well as the **Elk** and build-'em-yourself antennas - on the **ANTENNAS** page at work-sat.com.

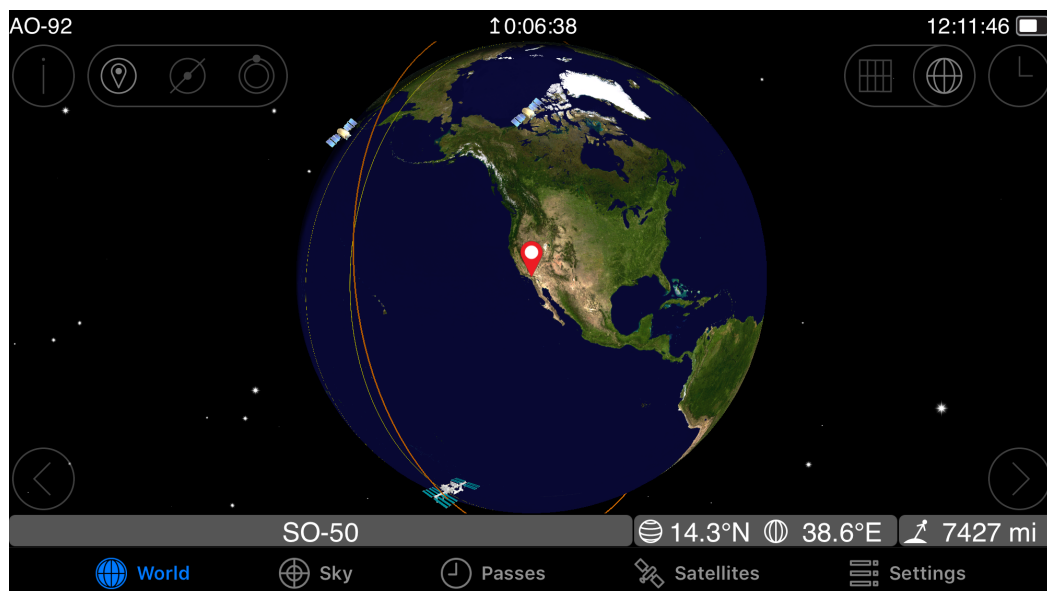
[5] - A .pdf copy of Icom's grid square map is available on the **SHACK AIDS** page at work-sat.com.

[6] - Download the ARRL's Handy Ops Guide from the **SHACK AIDS** page at - you guessed it - work-sat.com.



A – Alpha	J – Juliet	S – Sierra
B – Bravo	K – Kilo	T – Tango
C – Charlie	L – Lima	U – Uniform
D – Delta	M – Mike	V – Victor
E – Echo	N – November	W – Whiskey
F – Foxtrot	O – Oscar	X – X-Ray
G – Golf	P – Papa	Y – Yankee
H – Hotel	Q – Quebec	Z – Zulu
I – India	R – Romeo	

The International Telecommunications Union
Standard Phonetic Alphabet





Work-Sat.com

"Your Web site took me from zero knowledge to getting an HT and an Arrow. And just four months later, I have qualified for VUCC on the FM birds. A great site for the beginner on the birds. You un-mystify them."

"I love the site and I greatly appreciate the information you have provided to get me going! Yours is a no-nonsense approach to working satellites ..."

"Simplicity ... the idea of working sats "sounds complicated" but that's really not the case. You keep the language simple, illustrations simple, and concept simple ... give folks the idea that any ham can do this (which they can) with the right equipment ... if they follow the directions you provide."

K6LCS gave a fantastic presentation on amateur satellites. It was most informative and entertaining. Clint's passion for the subject was evident, and I would imagine that the club members individually and/or in a group will be eager to try satellite contact in the near future.

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ARISS
 Amateur Radio on the International Space Station



HT Programming for SO-50, AO-91, AO-92, and the ISS

(08/11/2019)

SO-50

Channel #	Alpha	TX Freq	TX Tone	RX Freq	RX Tone
501	50 +2	145.850	67.0	436.805	None
502	50 +1	145.850	67.0	436.800	None
503	50 74	145.850	74.4	436.795	None
504	SO-50	145.850	67.0	436.795	None
505	50 -1	145.850	67.0	436.790	None
506	50 -2	145.850	67.0	436.785	None

AO-91

911	AOS 2	435.240	67.0	145.960	None
912	AOS 1	435.245	67.0	145.960	None
913	AO-91	435.250	67.0	145.960	None
914	LOS 1	435.255	67.0	145.960	None
915	LOS 2	435.260	67.0	145.960	None

AO-92 U/v Mode (occasional L/v mode)

921	AOS 2	435.340	67.0	145.880	None
922	AOS 1	435.345	67.0	145.880	None
923	AO-92	435.350	67.0	145.880	None
924	LOS 1	435.355	67.0	145.880	None
925	LOS 2	435.360	67.0	145.880	None

ISS Frequencies

FM Voice - ITU Region 1		FM Voice - ITU Regions 2/3	
<i>Europe, Middle East, Africa, North Asia</i>		<i>N./S. America, Caribbean, Australia, S. Asia</i>	
145.800 downlink	145.200 uplink	145.800 downlink	144.490 uplink

FM SSTV downlink 145.800

AX.25 1200-baud packet 145.825

Clint Bradford K6LCS

work-sat.com

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AMSAT Engineering Documentation Update

Compiled by Jerry Buxton, N0JY
AMSAT Vice President - Engineering
n0jy@amsat.org

AMSAT, in consideration of the educational component of our organization, would like to release the majority of our design documentation to the public as a learning tool to anyone interested in satellite development. However, in order to avoid complications with ITAR and Export Administration Rules, as well as compliance with Non-Disclosure Agreements we have with our partners, and the need to keep command and control design secure in order to meet FCC and other governing agencies' regulations as well as protect our assets, we must redact certain information in some of the documents.

These AMSAT Space Symposium proceedings are intended to communicate the design and construction of our satellite projects with our members.

With the GOLF Program underway and GOLF-TEE the current project, the information in this year's Space Symposium Proceedings is about GOLF-TEE. As the project and program progress we will publish more of the information as well as photos. The publishing of this information over time also makes it available to anyone who wishes to use the designs or design ideas for their own satellites, hopefully with the intention of making more amateur radio satellites available to the world.

Because the documents are re-created here in their original form, minus any redactions, while some pagination of the originals was temporarily changed in order to provide the best readability there have been no additions regarding page numbers or the like since that is unknown until the Proceedings are published. To aid you in understanding what each page (figure) contains, the table below provides a brief description of each page (figure) of the documents following this introduction, in the order that you will find them.

FIGURE #	DOCUMENT NAME	ADDITIONAL INFO
1 - 12	GOLF-TEE System Requirements Specification	Some info is redacted (blacked out)
13 - 16	GOLF Series Satellite Active Warning	A "white paper" describing the background and reasons for audio/visual warning of satellite power activation.
17 - 19	GOLF-T DAS orientation vs orbit lifetime	An Excel reference to altitude vs. orbit lifetime for various GOLF-TEE orbits and attitudes. Used in requesting

		and determining suitability of various launch offers.
20 - 21	GOLF-T DAS random per KSC vs orbit lifetime	An Excel workup I asked Bob to do after learning from NASA that they consider worst-case scenario in that all deployables will fail, when they do their orbit lifetime assessment on an ELaNa mission spacecraft. Supersedes the above document to be used in requesting and determining suitability of various launch offers (including meeting our minimum acceptable lifetime, as well). It also looks for any opportunity to achieve the GOLF-1 “Greater Orbit” target altitude of 1100-1300 km and other possibilities ≥ 625 km given no suitable deorbit mechanism.
22	GOLF-T OVERVIEW concept 20180813	Mechanical design of the spacecraft as seen from several angles
23 - 24	GOLF-Tee Bus Lines	Avionics bus line (connector pin) assignments and nomenclature Some info is redacted
25 - 27	Golf-Tee Telemetry Data	Structure for the data to be sent in the telemetry beacon Some info is redacted
28	GOLF-TEE Subsystems Block Diagram	Some info is redacted

As with many projects, some documents are evolving so with the exception of the first four (figures 1 through 22) please consider them a “snapshot” taken for the Space Symposium Proceedings.

As you see in the document history of the System Requirements Specification it too undergoes periodic updates, although the current version represents the target for the flight unit very well. The functions of the GOLF-TEE satellite are not expected to be any more nor any less than are written in the current document, as “scope creep” is a certified killer of many a satellite project.

Date: October 5, 2019

Version: v2.4

GOLF-Tee

System Requirements Specification (SRS)

1 INTRODUCTION

The **GOLF** (Greater Orbit, Larger Footprint) CubeSat development program is AMSAT's follow-on program to its successful Fox-1 series of 1U CubeSat satellites. The Fox-1A through 1D satellite designs included single channel FM repeaters, while the Fox-1E includes a 30 kHz Linear Transponder, as their mission communication system. Now, **GOLF** will continue AMSAT's tradition of orbiting a series of satellites to fulfill the vision of "keeping amateur radio in space." By adopting a larger 3U form factor spacecraft platform, AMSAT is challenging its development team to take advantage of this increased spacecraft volume to generate more power, include advanced communications capabilities, and support increased numbers of sophisticated science/STEM experiments. Attitude control will be incorporated to support pointing high gain antennas, maximizing power generation, mitigating thermal conditions, and facilitating future propulsion.

To extend the GOLF program's name to an initial project designator, consider that a sportsman's golf outing begins at a tee. Analogously, AMSAT's initial GOLF project is a first outing "test" or "trial" endeavor, hence the project name "GOLF-Tee." The intent of the GOLF-Tee CubeSat designed spacecraft platform is to provide an on-orbit operational capability to prove-out/mature technologies to realize advanced space communications and experimentation support. Consequently, this document specifies the mandatory top level system requirements for the AMSAT GOLF-Tee satellite project.

1.1 Document History

DATE	VERSION	AUTHOR	CHANGE SUMMARY
October 30, 2017	v1.0	Jerry Buxton (N0JY)	Initial GOLF-TEE SRS draft
February 2, 2019	v2.0	Jerry Buxton (N0JY), Eric Skoog (K1TVV)	Changes to highlight mandatory "shall" requirements to scope the GOLF-Tee development and guide the Functional Performance Spec. details.
August 8, 2019	v2.1	Jerry Buxton (N0JY), Eric Skoog (K1TVV)	The addition of Satellite Active Control and Warning Requirements (Section 2.5)
September 6, 2019	V2.2	Jerry Buxton (N0JY)	Update 2.57, 2.58, 2.59 to allow for a range of frequency, and use of "warning tone" to replace "1 kHz tone".
October 5, 2019	V2.21	Jerry Buxton (N0JY)	No change to substance. Removed watermark, highlighting of 2.5.7, and corrected spelling of "mission" in intro.
October 5, 2019	V2.3	Jerry Buxton (N0JY)	Corrected objectives in part 5 Summary

October 5, 2019	V2.4	Jerry Buxton (N0JY)	Remove "and C band" from 3.7.2, redefine conditions/actions in 3.14.1 Transmit Inhibit Mode, 3.15.1 Beacon Duty Cycle change "start" to "end"
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1.2 Document Scope

The purpose of this document is to specify the mandatory requirements for the GOLF-Tee satellite at the system (i.e., "black box") level. It is intended to be used by hardware, software and mechanical designers to develop lower level specifications and Interface Control Documents (ICD). It is also intended to be used for test and integration planning.

1.3 Document Format

This document provides requirements in numbered format. Each requirement is assigned a unique number. Additional information such as comments or examples provided for guidance or clarity is *italicized* to distinguish it from specific requirements.

1.4 References

- a) AMSAT GOLF-TEE Satellite Concept of Operations, Version 1.21, March 3, 2018.
- b) CubeSat Design Specification, Rev. 13, February 20, 2014, The CubeSat Program Cal Poly SLO.
- c) Launch Services Program, Program Level Dispenser and CubeSat Requirements Document, LSP-REQ-317.01 Revision B, January 30, 2014, National Aeronautics and Space Administration (NASA).
- d) ITU Radio Regulations, Edition of 2016, available from <http://www.itu.int/publ/R-REG-RR-2016/en>

2 GENERAL REQUIREMENTS

2.1 CubeSat Requirements

- 2.1.1 The satellite shall satisfy the requirements specified in the CubeSat Design Specification (CDS), Rev. 13 for a 3U CubeSat.
- 2.1.2 The satellite shall satisfy the requirements specified in the NASA LSP-REQ-317.01 Revision B.
- 2.1.3 The satellite shall provide up to 400 g total mass for experiment payloads.
- 1.1.1 The satellite shall provide up to 90 x 90 x 24.0 mm total volume for experiment payloads.

2.2 Environmental Requirements

- 2.2.1 The satellite's subsystems shall be designed for an operating temperature range of - 40⁰ C to + 85⁰ C.
- 2.2.2 The satellite shall be designed to operate in an approximate 500 to 600 km, inclination ≥ 45 degrees, circular orbit.
- 2.2.3 The satellite shall be designed to tolerate the radiation environment in orbit.

2.3 Reliability Requirements

- 2.3.1 The satellite shall be designed for a 5-year mission supporting on-orbit lifetime.
- 2.3.2 The satellite shall be designed with "fail-soft" capabilities to allow "degraded mode" operation under abnormal conditions.

2.4 Radio Frequency (RF) Regulatory Requirements

- 2.4.1 The satellite's RF transmitters shall meet or exceed the requirements specified in ITU Radio Regulations, Volume 1 Articles, Chapter 1 – Terminology and Technical Characteristics of Stations, Article 3.
- 2.4.2 All satellite uplinks and downlinks shall be confined to the IARU allocated Amateur Satellite Service bands.
- 2.4.3 All satellite transmitter and receiver generated frequencies shall deviate by no more than 5 parts-per-million from their specified values including initial accuracy and temperature variation.
- 2.4.4 All satellite frequencies shall be coordinated with the IARU and the FCC.

The band plan with the actual IARU coordinated frequencies will be specified in a separate document.

2.5 Satellite Active Control and Warning Requirements



- 2.5.1 The satellite shall meet the Electrical Power Subsystem (EPS) power activation control and warning requirements specified in the section 1.4 b) and 1.4c) reference documents.
- 2.5.2 The satellite shall have two deployment switches on rail standoffs.
 - 2.5.2.1 The deployment switches shall be independent of each other.
 - 2.5.2.2 A single switch in the actuated state shall electrically disconnect the power system from the powered functions; this includes real time clocks.
 - 2.5.2.3 Both switches shall be in the unactuated state in order to connect power to the powered subsystems, including real time clocks.
- 2.5.3 When the satellite is configured for the orbital deployment startup sequence, the satellite shall wait a minimum of 50 minutes after the power is applied before actuating any deployables (CDS 3.4.4).
- 2.5.4 When the satellite is configured for the orbital deployment startup sequence, the satellite shall wait a minimum of 50 minutes after the power is applied before generating any RF signals (CDS 3.4.5).
- 2.5.5 The satellite shall have a red LED located in the area of the Remove Before Flight (RBF) pin in such a way that it is clearly visible through the RBF pin access port of the dispenser, as designated in CubeSat Design Specification Rev. 13.
- 2.5.6 Upon EPS activation, as a result of the removal of the RBF pin and both deployment switches entering the unactuated state, the red LED shall illuminate continuously.
 - 2.5.6.1 The red LED shall only illuminate when the satellite is configured for the orbital deployment startup sequence.
 - 2.5.6.2 Upon successful boot-up of the On Board Computer(s) (OBC) when the satellite is configured for the orbital deployment startup sequence, the OBC(s) shall assume control of the red LED and flash the red LED at an approximate interval of one second ON, one second OFF.
 - 2.5.6.3 The red LED shall extinguish when the EPS is disconnected from the powered subsystems by actuation of the deployment switches or insertion of the RBF pin.
- 2.5.7 The satellite shall have the capability to emit a warning tone with a frequency between 1 and 2 kHz at a level clearly audible outside of the orbital dispenser employed.
- 2.5.8 Upon EPS activation, as a result of the removal of the RBF pin and both deployment switches entering their unactuated state, the warning tone will be emitted.
 - 2.5.8.1 The warning tone shall only sound when the satellite is configured for the orbital deployment startup sequence.

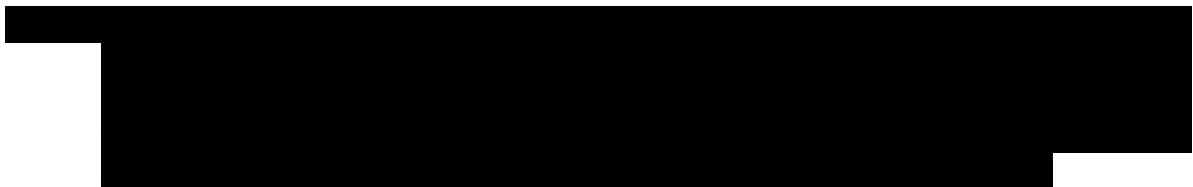


- 2.5.8.2 Upon successful boot-up of the OBC(s) when the satellite is configured for the orbital deployment startup sequence, the OBC(s) shall assume control and modulate the warning tone at an approximate interval of one second ON, one second OFF.
- 2.5.8.3 The warning tone on interval shall be synchronous with the red LED ON interval.
- 2.5.8.4 The warning tone shall cease when the EPS is disconnected from the powered subsystems by actuation of the deployment switches or insertion of the RBF pin.
- 2.5.8.5 The warning tone shall be muted by an external command received via the satellite's umbilical port only when the umbilical is connected to an external device for development testing or diagnostics.
- 2.5.8.6 The warning tone shall be muted when external power is applied to the satellite for charging.
- 2.5.9 Flashing of the red LED and sounding of the warning tone shall be terminated by the OBC(s) after successful completion of the orbital deployment startup sequence as a power saving measure.

3 FUNCTIONAL REQUIREMENTS

3.1 Attitude Determination and Control (ADAC)

- 3.1.1 The satellite shall provide 3-axis active stabilization via an ADAC subsystem.



3.2 Access Ports

- 3.2.1 The satellite shall include a "Remove Before Flight" (RBF) pin as per the CubeSat Design Specification.
- 3.2.2 The satellite shall include an umbilical port as per the CubeSat Design Specification.

3.3 Pre-launch Features

- 3.3.1 The satellite's battery and solar panels shall be electronically disconnected from the avionics when the "Remove Before Flight" pin is inserted, regardless of the state of the deployment switches.
- 3.3.2 The satellite shall provide a means to externally charge the battery via a charging port while integrated with the dispenser.

- 3.3.3 The satellite shall provide a means to run diagnostic tests via an umbilical cable port while integrated with the dispenser.

3.4 Power

- 3.4.1 GOLF-Tee's Electrical Power Subsystem (EPS) shall provide conditioned, regulated, and distributed DC power sourced by solar panel arrays. Energy storage shall be provided via battery packs charged, protected, and monitored by a battery management system.
- 3.4.2 The satellite shall produce electrical power from sunlight.
- 3.4.3 The satellite shall produce electrical power while in sunlight regardless of orientation and while tumbling or spinning.
- 3.4.4 The satellite shall produce sufficient average electrical power to operate continuously in the orbit of maximum eclipse.
- 3.4.5 The satellite shall provide sufficient battery capacity to operate continuously in the orbit of maximum eclipse.

3.5 On Board Computers (OBC)

- 3.5.1 GOLF-Tee shall include a Legacy Internal Housekeeping Unit (LIHU) OBC that has exhibited a Technology Readiness Level of nine (TRL 9) and is capable of providing high reliability telemetry, command, and control of the satellite.
- 3.5.2 GOLF-Tee shall also include a Radiation-Tolerant Internal Housekeeping Unit / Digital Command and Telemetry (RT-IHU/DCT) OBC.

3.6 Experiment

- 3.6.1 GOLF-Tee shall include a Vanderbilt University Low Energy Proton experiment and controller. The OBCs shall collect and relay experiment data to ground stations as agreed to between Vanderbilt University and AMSAT.
- 3.6.2 The satellite shall provide DC power for an experiment payload.
- 3.6.3 The satellite shall provide a means to activate and deactivate experiment payloads and control their operational duty cycles.

The experiment payload details will be specified in a separate document.

3.7 RF Uplink(s)

- 3.7.1 The satellite shall provide uplink receivers.
- 3.7.2 The RF uplink receivers' primary frequencies of operation shall be on VHF Amateur Satellite Service allocated frequencies.

3.8 RF Downlink(s)



- 3.8.1 The satellite shall provide downlink transmitters.
- 3.8.2 The RF downlink transmitters' primary frequencies of operation shall be on UHF and X-band Amateur Satellite Service allocated frequencies.
- 3.8.3 The downlink transmitters shall generate intermodulation products no higher than - 20 dBc when operating at maximum output power.

3.9 Transponder(s)

- 3.9.1 GOLF-Tee shall provide linear transponder (LT) operation on VHF uplink and UHF downlink Amateur Satellite Service allocated frequencies.
 - 3.9.1.1 The V/u transponder shall have a 3 dB bandwidth of 30 kHz and a 20 dB bandwidth of 50 kHz, referenced to the center of the passband.
 - 3.9.1.2 The V/u transponder shall be an inverting transponder. The transponder shall have a means of sensing and adjusting gain so that the highest level transponded signal is not distorted with intermodulation products higher than - 20 dBc with multiple signals in the passband.
 - 3.9.1.3 The transponder gain adjustment shall have a time constant of **<TBD>** seconds, such that the highest level signal in the passband will not 'pump' other signals in the passband by its modulation.
 - 3.9.1.4 The transponder shall exhibit a linear gain such that a received CW signal of **<TBD>** dBm will result in an RF power output of +26 dBm. Any other signals amplified in the passband and sharing this output level shall create IMD products not to exceed -20 dBc in the passband of the transponder.
- 3.9.2 The satellite shall provide a digital transponder employing software defined radio (SDR) technology.
 - 3.9.2.1 The transponder shall support input RF signals with modulation formats received in accordance with a (TBD) Frequency Division Multiple Access (FDMA) band plan.
 - 3.9.2.2 The SDR shall provide a capability to transmit a satellite telemetry and experimental data downlink at a minimum rate of 1 Mbps in the 10 GHz amateur satellite service band.
 - 3.9.2.3 Input RF signals shall be transponded to the X-band Amateur Satellite Service allocated frequencies.

3.10 Deployables

- 3.10.1 The satellite shall provide deployable solar array wing (SAW) panel assemblies. The total solar panels' power generation capacity shall be sufficient to furnish the necessary power to operate the Attitude Determination and Control (ADAC) subsystem, the user transponders (including telemetry), the OBCs, and other required functions such as power conditioning and distribution.
- 3.10.2 GOLF-Tee shall provide deployable omnidirectional antennas for the VHF and

UHF bands.

- a.) The antennas shall be used with the linear transponder.
- b.) The antennas shall be designed to support telemetry, command, and control reception as well as nominal linear transponder use if the satellite is in random attitudes, e.g., tumbling due to lack of attitude control.

3.10.3 GOLF-Tee shall provide a deployable multi-band antenna for amateur radio satellite service allocated frequencies in the L, S, and C bands including GPS L-band signals.

3.10.4 The GOLF-Tee satellite shall include a CubeSat Terminator Tape deorbit device as a deployment experiment.

3.11 Telemetry/Experiment Data

3.11.1 The satellite shall measure and store telemetry data to quantify its health and status.

3.11.2 The satellite shall also collect and store data generated by the hosted experiment(s).

3.11.3 Telemetry and experiment data shall be stored for downlinking as Whole Orbit Data (WOD).

3.11.4 The telemetry data shall include as a minimum, the measured parameters shown in Table 1 below:

PARAMETER NAME	DESCRIPTION
CELL V	Voltages of battery packs
PANEL V	Voltages of solar panels
TOTAL I	Total DC current out of power system
PA I	DC current into RF transponders' power amps
BATTERY T	Temperature of battery
PANEL T	Temperatures of solar panels
TX T	Temperature of RF transponders' transmitters
RX T	Temperature of RF transponders' receivers

TABLE 1 – Directly Measured Telemetry Parameters

- 3.11.5 The telemetry measured parameters shall be sampled at least every 15 seconds.
- 3.11.6 The minimum and maximum values of each of the measured parameters shall be saved in non-volatile memory.
- 3.11.7 The telemetry data shall also include as a minimum, the calculated parameters shown in Table 2 below:

PARAMETER NAME	DESCRIPTION
UP TIME	Total seconds since initial orbit power-up or the last reset
SPIN	Satellite spin rate and direction
ORIENTATION	Satellite's orbital orientation [ref. frame <TBD>]

TABLE 2 – Calculated Telemetry Parameters

- 3.11.8 A telemetry frame shall include the current measured values, the saved minimum and maximum values, and the current calculated values.

3.12 Telemetry Transmission

- 3.12.1 The satellite shall send telemetry using BPSK on a UHF RF downlink frequency. The downlink telemetry signal shall be a 1200 bps BPSK signal located outside the user V/u transponder passband.
- 3.12.2 The telemetry signal's peak power level shall be approximately +20 dBm.
- 3.12.3 Telemetry data shall be transmitted simultaneously with user transponded signals or by itself.
- 3.12.4 Telemetry transmission frames shall include telemetry and experiment data.

3.13 Command Capability

- 3.13.1 The satellite shall provide a means to process commands sent via the VHF (or other) RF uplink from authorized AMSAT ground control stations.
- 3.13.2 The command receiver shall operate on a dedicated frequency outside the user V/u transponder's operating bandwidth frequencies.



3.13.5 The command uplink receiver will not be responsible for bit or byte synchronization, re-timing, or error correction.

3.13.6 As a minimum, the satellite shall recognize the following received commands, shown in Table 3, below.

Command	Operation
SAFE MODE	Enter Safe Mode
INHIBIT TX	Inhibit ALL RF transmissions
ENABLE TX	Enable ALL RF transmissions
OBC OFF	Power off OBC (LIHU and/or RT-IHU/DCT)
OBC ON	Power on OBC (LIHU and/or RT-IHU/DCT)
CLEAR	Clear stored telemetry
ENABLE TRANSPONDER	Enable Transponder (SDR and/or LT)
DISABLE TRANSPONDER	Disable Transponder (SDR and/or LT)
ENABLE AUTO-SAFE	Enable Auto-Safe Mode
DISABLE AUTO-SAFE	Disable Auto-Safe Mode

TABLE 3 – Ground Station Commands

3.13.7 A SAFE MODE command shall cause the satellite to enter the Safe Mode.

3.13.8 An INHIBIT TX command shall disable all RF transmitters.

3.13.9 An ENABLE TX command shall enable all RF transmitters.

3.13.10 An OBC OFF command shall cause any or all OBCs to power off.

3.13.11 An OBC ON command shall cause any or all OBCs to power on.

3.13.12 A CLEAR command shall cause the satellite to clear the saved minimum and maximum telemetry parameter values.

3.13.13 An ENABLE TRANSPONDER command shall cause the satellite to enable Transponder functioning (SDR and/or LT).

3.13.14 A DISABLE TRANSPONDER command shall cause the satellite to disable Transponder functioning (SDR and/or LT).

3.13.15 An ENABLE AUTO-SAFE command shall enable the auto-safe mode state.

3.13.16 A DISABLE AUTO-SAFE command shall disable the auto-safe mode state.

Exact control interface details will be specified in a separate document.

3.14 On-Orbit Operating Modes

3.14.1 The satellite shall provide operating modes shown in Table 4 below:

NAME	CONDITIONS/ACTIONS
Umbilical Mode	On the bench, under engineering development and test conditions with umbilical cord plugged and external power applied via a charging cable.
Dispenser Secure Mode	Integrated into a Launch Vehicle dispenser with the RBF pin pulled and separation switches actuated. Can be charged and diagnostics run IF those ports are accessible.
Initial Orbit Mode	Released from dispenser; waits ≥ 50 minutes before deploying antennas, solar panels and beginning RF transmissions.
Beacon Mode	Initial limited telemetry transmissions on 2 minute duty cycle containing critical satellite's health status data
De-Tumble Mode	Activation of satellites Coarse Sun Sensors (CSS), Inertial Measurement Units (IMU), and Magnetorquers to stabilize the platform by eliminating initial 3-axis spinning.
Attitude Control Mode	Solar Panel Array Wings and multi-band antenna deployment. ADAC subsystem fully powered and Flight Computer commands attitude sensing and orientation actuators to achieve Sun-Pointing vector – Start of Commissioning actions.
Transponder Mode	User passband channel and telemetry/experiment active for SDR and/or LT transponding.
Telemetry Mode	Telemetry only transmissions; increased data and data rate for TLM and Experiment data.
Safe Mode	When commanded, non-critical satellite subsystems shut down and limited telemetry transmitted on a 2 minute duty cycle.
Auto Safe Mode	If enabled, detection of a low battery condition automatically activates Safe Mode.
Transmit Inhibit Mode	When commanded, cease ALL RF transmissions per Title 47 Part 97 §97.207(b) Code of Federal Regulations
Degraded Mode	Preplanned partial function execution resulting from various failure scenarios.

TABLE 4 – ON-Orbit Operating Modes

3.14.2 The satellite shall transition between its on-orbit operational modes as shown in the Operational Modes Diagram in Figure 1 below.

<<Jay Amirmokri's VISIO Operational Modes Diagram>>

3.15 Operational Timing Requirements

3.15.1 The satellite shall satisfy the operational times shown in Table 5 below:

FUNCTION	TIME ($\pm 5\%$)	OPERATIONAL CONDITIONS
Burn Resistor Activation	≈ 5 seconds	Time allotted for the (activated) burn resistors' initial melting of the deployable Solar Panel, antenna, and deorbit device restraints.
Burn Resistors RE-activation	≈ 20 seconds	Time allotted for the (RE-activated) burn resistors' subsequent melting of the deployable antenna restraints.
Antenna/RF Initiation Delay	≈ 50 minutes	Antenna deployment and transmission inhibit time after dispenser launch.
Beacon (Safe Mode) Duty Cycle	≈ 2 minutes	Elapsed time from end of beacon telemetry transmission to start of next beacon transmission while in SAFE MODE.
Telemetry Period	<15 seconds	Sampling period for all telemetry parameters.
ENABLE TX Confirm	≈ 3 minutes	Time after receipt of ENABLE TX command before transmitting a telemetry beacon.
Watchdog Timer	≈ 10 seconds	If OBC-directed tasks do not report back within this time period, the satellite will reset.

TABLE 5 – Operational Times

4 EXTERNAL INTERFACE DOCUMENTS

To fully specify the satellite's technical requirements, the following documents should be consulted:

- a. IARU Coordinated Frequency Plan
- b. Downlink Specification
- c. Control Interface Specification
- d. Experiment Payload Specification

5 SUMMARY

The GOLF-Tee satellite will be AMSAT's first 3U CubeSat. Its primary mission objectives are to validate the on-orbit performance of the ADAC and EPS subsystems, and to gain initial orbit and space radiation exposure for radiation event-induced fault mitigation by the RT-IHU. A secondary objective is to develop and test a minimum speed of 1 megabit per second data (telemetry) downlink in the 10 GHz band.

GOLF SERIES

SATELLITE ACTIVE WARNING

From the CubeSat Design Specification

3.3.1 The CubeSat power system shall be at a power off state to prevent CubeSat from activating any powered functions while integrated in the P-POD from the time of delivery to the LV through on-orbit deployment. CubeSat powered function include the variety of subsystems such as Command and Data Handling (C&DH), RF Communication, Attitude Determine and Control (ADC), deployable mechanism actuation. CubeSat power systems include all battery assemblies, solar cells, and coin cell batteries.

3.3.2 The CubeSat shall have, at a minimum, one deployment switch on a rail standoff, per Figure 7.

3.3.3 In the actuated state, the CubeSat deployment switch shall electrically disconnect the power system from the powered functions; this includes real time clocks (RTC).

3.3.4 The deployment switch shall be in the actuated state at all times while integrated in the PPOD.

3.3.5 If the CubeSat deployment switch toggles from the actuated state and back, the transmission and deployable timers shall reset to $t=0$.

3.3.6 The RBF pin and all CubeSat umbilical connectors shall be within the designated Access Port locations, green shaded areas shown in Appendix B.

3.3.7 The CubeSat shall include an RBF pin.

3.3.7.1 The RBF pin shall cut all power to the satellite once it is inserted into the satellite.

3.3.7.2 The RBF pin shall be removed from the CubeSat after integration into the P-POD.

Discussion

Note that 3.3.2 is the minimum requirement as the CDS is a guideline and no missions we have flown allowed less than 2 switches. So the use of deployment switches below means all of whatever number we have.

As we see in 3.3.1 everything must be quite dead when we are in the integrated state. Tony's original Fox-1 design, which carried through the series mostly because we were able to talk a waiver with some math demonstration on solar illumination and by extending the effective actuated state of the switches after they opened, was designed for our lowest risk in actuation upon P-POD deploy. But even by the time Fox-1A was completed the conditions had changed enough that we were just squeaking by the LSP requirements and that got tougher with the rest. So now, CubeSat requirements have matured to be very specific and the absolute lowest

risk to the LV, primary payload, and other CubeSats in the same P-POD. That raises our risk of not activating properly but you don't get to make the rules when you hitchhike, eh?

The purpose of the Satellite Active Warning on the GOLF series (and whatever other CubeSats we might build) is to alert us and the launch integrator to the fact that CDS 3.3.1 has been violated whether by the RBF function or the deployment switches function, it doesn't matter. If any powered functions are getting power whether one or all, it is a violation. During the entire time we are integrated in the P-POD (or other deployer) starting when the RBF is pulled, if the CubeSat powers up it not only violates the requirement but it puts other things at risk should it release any deployables or begin transmitting RF. That can really ruin the fun for everybody. The warning also lets us know if the CubeSat powered up during any of the environmental tests that simulate the launch, so we can hopefully shut it down before it does any damage as well as go back to the bench and figure out what went wrong. Even if we physically survived the test, we fail the overall objective if the launch is going to cause us to power on.

If you recall the discussion from a few weeks ago, you know that we included information on how Fox-1 was designed and what it did in regard to the Satellite Active Warning. I think that was actually designed more around the usefulness to us in testing than the end game of integration, probably since the CDS nor so far any LV ICD I have seen have any requirement to warn. However, it is just good practice to include it and Fox-1 had a pretty good idea in that it used both audio and visual warnings. But it was entirely based on the activation of the IHU to indicate that power was applied, and while that was basically OK for Fox-1, like some of the other Fox-1 design it wasn't really thorough in respect to satisfying CDS. Power could be applied and IHU dead for whatever reason, and the radio could still be operating on its own because that was a backup designed in, to be able to have a repeater even when everything else but the power systems failed. That is why AO-85 works in "COR mode" now.

Bringing together the relevant parts of the CDS, that will be at least the minimum required in GOLF CubeSats, and the points from the discussion on the GOLF meeting, I propose that the following be incorporated into the System Requirements for GOLF-TEE and GOLF-1. These requirements (as finalized by the team) will apply as well to any other GOLF series satellites unless the relevant parts of the CDS are changed, the CDS revision changes, or we discover better implementation during the design and construction of GOLF-TEE/GOLF-1.

(I used bullets instead of numbering as this is not set in the requirements yet.)

Requirements

CubeSat Requirements

- The satellite shall meet the requirements specified in the CubeSat Design Specification Rev. 13.
- The satellite shall have two deployment switches on rail standoffs.
 - The deployment switches shall be independent of each other.

- A single switch in the actuated state shall electrically disconnect the power system from the powered functions; this includes real time clocks (RTC).
 - Both switches shall be in the unactuated state in order to connect the power system to the powered functions, including real time clocks (RTC).
- (CDS 3.4.4.) When the satellite is configured for the orbital deployment startup sequence, the satellite shall wait a minimum of 50 minutes after the power is applied before actuating any deployables.
- (CDS 3.4.5) When the satellite is configured for the orbital deployment startup sequence, the satellite shall wait a minimum of 50 minutes after the power is applied before generating any RF signals.
- The satellite shall meet the requirements specified in the NASA LSP-REQ-317.01 Revision B.

‘Satellite Active’ Warning

- The satellite shall have a red LED located in the area of the RBF pin in such a way that it is clearly visible through the RBF pin access port of the P-POD, as designated in the CubeSat Design Specification Rev. 13.
- Upon the application of the power system to powered functions by the removal of the RBF pin and both deployment switches entering the unactuated state, the red LED shall illuminate.
 - The red LED shall only illuminate when the satellite is configured for the orbital deployment startup sequence.
 - Upon successful startup of the IHU when the satellite is configured for the orbital deployment startup sequence, the IHU shall assume control of the red LED in and flash the red LED at the interval of one second on, one second off.
 - The red LED shall extinguish when the power system is disconnected from the powered functions by actuation of the deployment switches or insertion of the RBF pin.
- The satellite shall have the capability to sound a 1 kHz tone that is audible outside of the orbital deployer used for the mission.
- Upon the application of the power system to powered functions by the removal of the RBF pin and both deployment switches entering the unactuated state, the tone will sound.
 - The tone shall only sound when the satellite is configured for the orbital deployment startup sequence.
 - Upon successful startup of the IHU when the satellite is configured for the orbital deployment startup sequence, the IHU shall assume control of the tone and activate the tone at the interval of one second on, one second off.
 - The tone on interval shall match the red LED on interval.
 - The tone shall cease when the power system is disconnected from the powered functions by actuation of the deployment switches or insertion of the RBF pin.

- The tone may be muted by external command via the satellite umbilical port only, when the umbilical is connected to an external device for testing or diagnostics.
- The tone may be muted by external command via the satellite umbilical only, when external power is applied to the satellite for charging, testing, or diagnostic purposes.
- Flashing of the red LED and sounding of the 1 kHz tone shall be terminated by the IHU after successful completion of the orbital deployment startup sequence, as a power saving measure.

Requirements comments

The application of power to the powered functions can begin when the deployment switches are unactuated (RBF pin out, of course). For our Fox veterans as well as newcomers, we implemented a ~90 second delay between deployment switches being unactuated and power being applied with the Fox-1 satellites as a workaround to the nearly instantaneous no-turning-back application of power of the Fox-1 design, which violated the CDS and other documents by delivery time. (The RBF could be inserted to stop the activation, but that is irrelevant once the satellite was integrated.) I do not know if the requirement had changed after the design was made, or the design was chosen to give the best insurance that the thing would turn on (for good) once the switches opened, but it sucked when the rubber hit the road even with Fox-1A. I asked for the 90 seconds when we prepared Fox-1C/D for our second (at the time) launch because the deployer on that flight had no access panels like the P-POD does, requiring the RBF pin to be pulled before the deployment switches are closed by dropping the CubeSat into the deployer tube. The 90 seconds gave me time to pull the pin and do the careful insertion of the CubeSat into the deployer so that the switches were properly seated and actuated. It also turned out that Spaceflight had to pull the pin on Fox-1D because the final integration for our deployer was done on site in India just before the launch, so that gave comfort to them being their first time with a ticking Fox.

Sticking to the CDS in the application of that requirement eliminates the need for a delay when the timers are reset to $t=0$ (per CDS) by actuating one or both deployment switches. While the red lights and siren would sound during a similar integration like Fox-1D, the 50 minute delay keeps anything from happening. In fact the design now gives immediate feedback when the deployment switches are activated again through the cessation of the lights and noise, while the 90 second delay left you in suspense until that timed out before you could verify that the bird was not activated and was properly powered off. The current design also gives a bit more feedback in any integration because it will warn immediately if the switches are unactuated which was always another bit of suspense in having to wait for the light/sound up until 90 seconds after the dispenser was closed and secured.

So glad to be rid of the circuitry needed for the Fox-1 power activation and the explanations of this very odd design at integration!

DAS 2.1.1.1

solar_flux retrieved June 11, 2018.

Launch	2020.5
RAAN	0°
ArgPer	0°
Mass	3.98 kg

(target 20 grams under 4kg limit)

Orbit Lifetime, years

	500 km		550 km		575 km		600 km		625 km		650 km		700 km		750 km	
	m ²	m ² /kg	97.4°	60.0°	97.6°	60.0°	97.7°	60.0°	97.8°	60.0°	97.9°	60.0°	98.0°	60.0°	98.2°	60.0°
Min (end) area	0.011	0.00272	11.997	12.189	24.471	24.860	35.647	36.271	53.958	55.239	76.561	78.620	100	100	100	100
(side) area	0.035	0.00888	2.771	2.825	5.169	5.421	11.893	12.134	14.467	14.795	23.348	23.797	33.517	34.196	65.166	66.661
simple average area	0.088	0.02207	1.648	1.692	2.502	2.585	3.149	3.269	4.101	4.326	7.403	10.344	12.879	13.246	24.389	26.122
Max (array) area	0.140	0.03526	1.309	1.342	1.944	1.999	2.366	2.442	2.930	3.034	3.713	3.888	5.322	5.996	14.177	14.664

1100 km	
m ²	m ² /kg
GOLF-1 in 2021.5	63.4°
GOLF-1 simp.ave	100
side.area + TermTape	100
simp.ave + TermTape	100
+ 2 TermTapes	100

2019.5 2020.5 **2021.5** 2022.5 2023.5 2024.5 2025.5 2026.5 2027.5 2028.5 2029.5 2030.5 2031.5
vs yr 23.661 22.746 21.963 21.689 21.64 21.591 21.498 21.35 21.284 21.886 22.73 22.292 21.837

Conclusions (KF4KSS 20180612, GOLF-T CSLI followup):

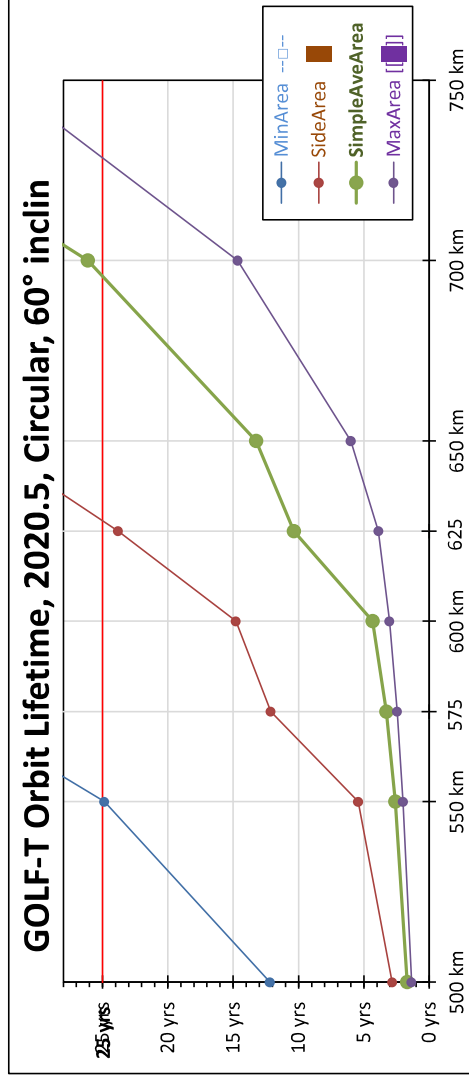
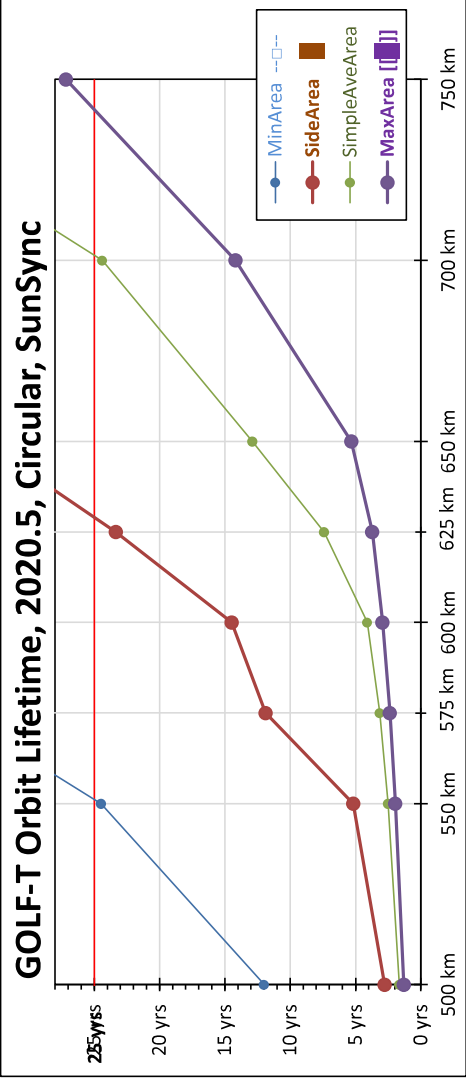
SideArea is likely cross-section if SunSync 6AM/6PM (terminator).

MaxArea is likely cross-section if SunSync Noon/Midnight.

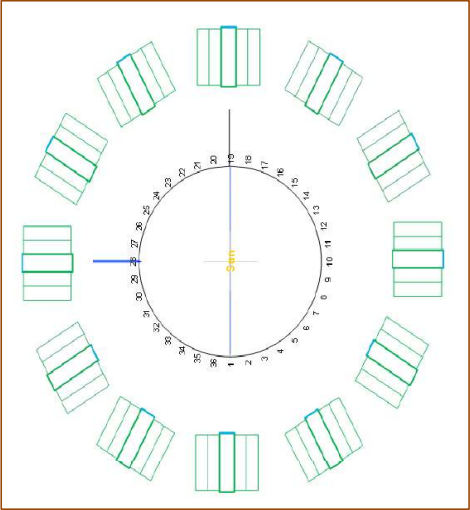
SimpleAverageArea is likely cross-section for all other scenarios, but with wide variance and low confidence due to simplifications/assumptions.

Altitude <**600 km** risks <**5 years** orbit lifetime, except special case of SunSync 6AM/6PM.

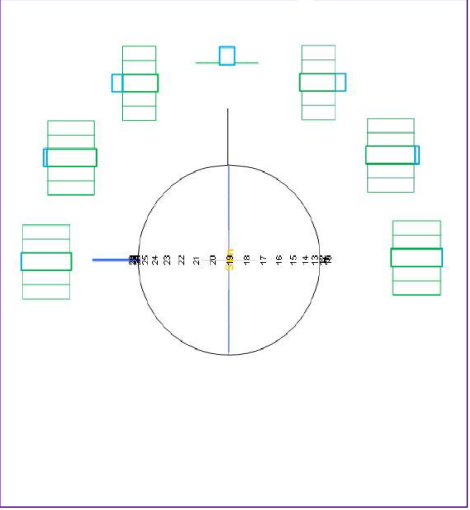
Altitude >**625 km** risks >**25 years** orbit lifetime in special case of SunSync 6AM/6PM, yet could still be only **4 years** in special case of SunSync Noon/Midnight. **Very** dependent on orientation.



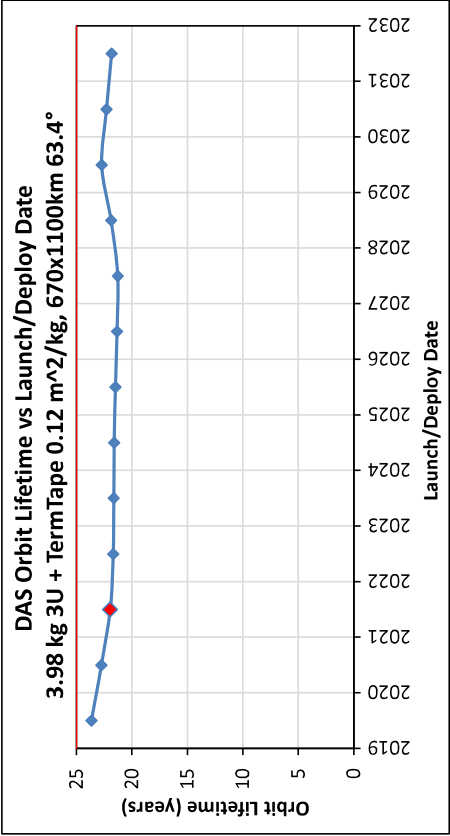
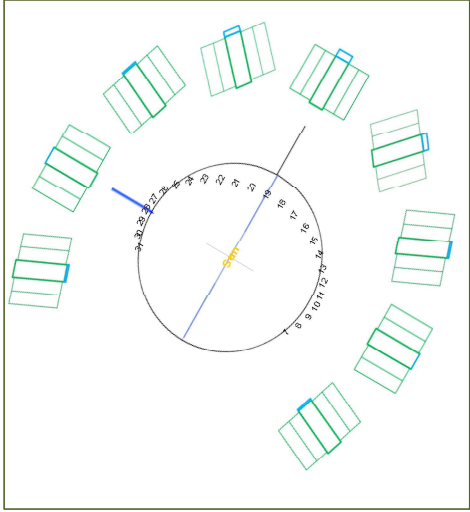
SideArea (array edge is toward orbit velocity vector)



MaxArea (array is sweeping thru orbit velocity vector)



SimpleAveArea (array varies wrt orbit velocity vector)



"Worst Case" orbit lifetime of AMSAT's GOLF-TEE.

Assume deployables don't deploy, and random tumble orientation.

Explore likely orbits to report altitudes that max out the 25 year requirement.

Start Year	2020.5	DAS input
R.A. of A.N.	0 deg	DAS input
Arg of Peri	0 deg	DAS input
Mass	4.0 kg	This is worst-case since lighter would actually de-orbit slightly faster.
X width	0.1032 m	100mm + 2 PCBs
Y width	0.112 m	100mm + 6 PCBs
Z length	0.34 m	
X area	0.0381 m ²	Y*Z
Y area	0.0351 m ²	X*Z
Z area	0.0116 m ²	X*Y
Random tumble, average projected area	0.0424 m ²	=3/2*side for cube, so extend as =3/2*(Xarea/3+Yarea/3+Zarea/3). source: https://math.stackexchange.com/questions/1365486/expected-value-of-cube-projection
Area-to-Mass	0.0106 m ² /kg	DAS input

Using DAS, find circular altitude resulting in 25 years for inclination of 63.4 degrees.

Altitude 643.6 km DAS result (actually 24.986 yrs)

Using that altitude as average for eccentric orbit, using DAS, find out if eccentricity generally increases or decreases orbit lifetime.

Eccentricity	0.02	arbitrary but realistic eccentricity.
Earth radius	6371 km	
Perigee Alt	503.308 km	DAS input
Apogee Alt	783.892 km	DAS input
Orbit lifetime	14.428 yr	DAS result

Therefore, modifying a circular orbit into an eccentric orbit causes earlier demise.

Using DAS, find perigee resulting in 25 years when apogee is 1100km and inclination of 63.4 degrees.

Perigee 474.5 km DAS result (actually 24.991 yrs)

where the circular 1100 km lifetime > 100 years (max DAS calc).

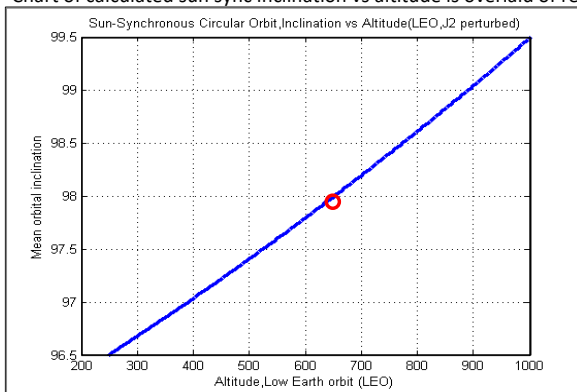
Changing inclination from 63.4 to sun-sync, using DAS, find circular altitude for 25 years.

Altitude	647.4 km	DAS input (iteratively input for target result of 25 years)
Eccentricity	0	
Sun sync ecc.	97.947 deg	DAS input (calc based on iterative altitude)
Orbit lifetime	24.986 yr	DAS result

Therefore, inclination change between 63.4 and sun sync doesn't change orbit lifetime enough to affect preliminary discussions.

Ref chart not used but validates simpler inclination calc, <https://smallsats.org/2013/04/11/sun-synchronous-circular-orbit/>

Chart of calculated sun sync inclination vs altitude is overlaid of ref chart below.



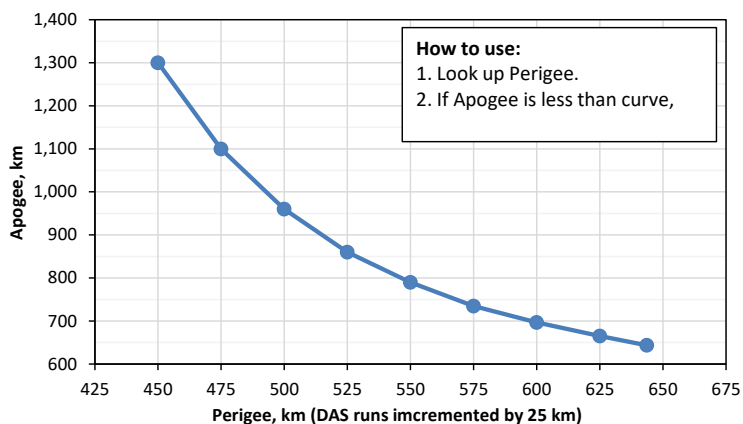
Notice how steep orbit lifetime is with altitude.

circular alt	lifetime
575.	10.59
600.	13.546
625.	21.01
650.	26.47

Additionally, what combos of perigee & apogee result in orbit lifetime 25 years (inclination 63.4 degrees)?

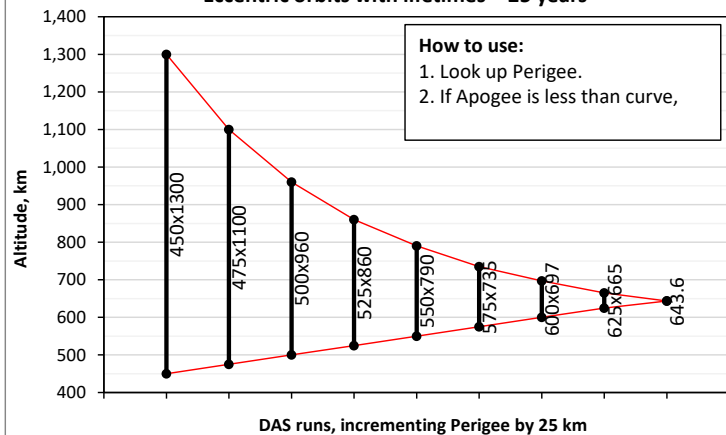
	perigees	apogees	lifetime	run	average	eccentric.	table re-ordered for charting purposes	
450x1300	450.	1300.	24.942	1	875.	0.28	1	450.
475x1100	475.	1100.	25.073	2	787.5	0.22	1	1300.
500x960	500.	960.	25.079	3	730.	0.17		
525x860	525.	860.	24.991	4	692.5	0.13	2	475.
550x790	550.	790.	24.997	5	670.	0.09	2	1100.
575x735	575.	735.	24.827	6	655.	0.06		
600x697	600.	697.	24.975	7	648.5	0.04	3	500.
625x665	625.	665.	25.008	8	645.	0.02	3	960.
643.6	643.6	643.6	24.986	9	643.6	0.00		

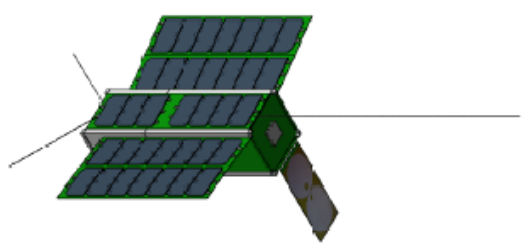
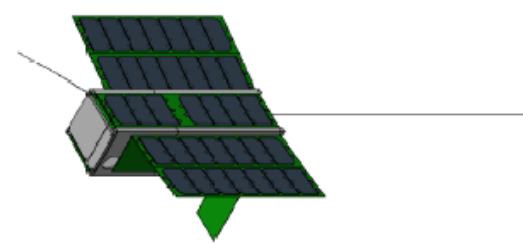
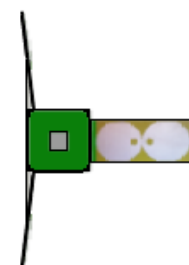
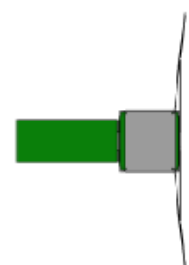
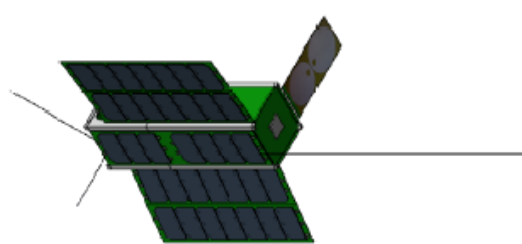
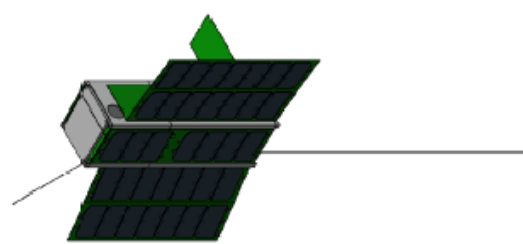
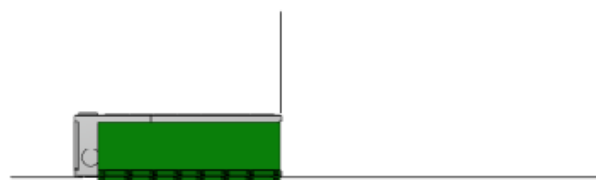
Eccentric orbits with lifetimes = 25 years



4	525.
4	860.
5	550.
5	790.
6	575.
6	735.
7	600.
7	697.
8	625.
8	665.
9	643.6
9	643.6

Eccentric orbits with lifetimes = 25 years





GOLF-Tee Bus Lines

NOTE: BLACKED OUT CELLS CONTAIN REDACTED INFORMATION (ITAR, NDA, PROPRIETARY, OR COMMAND/CONTROL)

Version 1.5 WB1FJ, 20-Sep-2019

Pin No.	For Golf-1	NAME	TYPE	VOLTAGE	SOURCE	SINK	NOTES	Golf-T IHU Switched
1	Available	L1	Digital	0 & 3 Volts	LIHU	RT-IHU	IHU Coordination—To RT-IHU	*
2	Available	TX_PA_CURRENT	Analog	0 to 3 Volts	RX/TX	LIHU	LT Power Amplifier current consumption	Legacy Only
3		SPI1_SCK1	Digital	0 & 3 Volts	LIHU	RX/TX	SPI1 Bus Slave Clock TLM data modulator	Legacy Only
4	Available	TX_TEMP	Analog	0 to 3 Volts	RX/TX	LIHU	RX/TX Card's Power Amplifier temperature	Legacy Only
5		SPI1_MISO	Digital	0 & 3 Volts	RX/TX	LIHU	SPI Bus Master In, Slave Out from TLM modulator	Legacy Only
6	Available	Available						
7		SPI1_MOSI	Digital	0 & 3 Volts	LIHU	RX/TX	SPI Bus Master Out, Slave In to the TLM modulator	Legacy Only
8	Available	VGA_CNTL	Analog	0 to 3 Volts	RX/TX	LIHU	RX/TX generated control voltage to the receiver's Variable Gain Amplifier (VGA)	Legacy Only
9	Available	LIHU Console Rx	Digital	1 and 3 V	LIHU	CIU	LIHU Console Serial Receive	Legacy Only
10	Available	ICR_RSSI	Analog	0 to 3 Volts	ICR	LIHU	Analog Received Signal Strength Indicator (RSSI) from the Cmd Rcvr	Legacy Only
11	Available	LIHU Console Tx	Digital	1 and 3 V	LIHU	CIU	LIHU Console Serial Transmit	Legacy Only
12	Available	TLM_Data	Digital	0 & 3 Volts	LIHU	RX/TX	Telemetry data to be transmitted on the TLM downlink channel; level should be adjusted for best TLM decoding.	Legacy Only
13		EXP1_ENABLE	Digital	0 & 3 Volts	IHU	EXP 1	HIGH = Enable Experiment Card #1	Y
14	Available	Available						
15	Exp2_Enable	R0	Digital	0 & 3 Volts	RTIHU	LIHU	IHU Coordination from RT-IHU	*
17	EXP3_Enable	L0	Digital	0 & 3 Volts	LIHU	RT-IHU	IHU Coordination to RT-IHU	*
19	EXP4_Enable	R1	Digital	0 & 3 Volts	RT-IHU	LIHU	IHU Coordination from RT-IHU	*
21		Serial SDR Rx	Digital	0 & 3 Volts	CIU/SDR	IHU	Serial Receive Channel; ASYNC, Mark High ^[1]	Y
23		I2C1_SCK	Digital	0 & 3 Volts	IHU	CIU	I ² C Standard Bus #1 Clock (Bidirectional): IHU Master and deploy slave	Y
25		I2C1_SDA	Digital	0 & 3 Volts	IHU	CIU	I ² C Standard Bus #1 Clock (Bidirectional): IHU Master and deploy slave	Y
26	Available	RX/TX_CNTL	Digital	0 & 3 Volts	IHU	RX/TX	HIGH = IHU is running and in control; LOW = RX/TX functions "Autonomously"	Y
27		Serial SDR Tx	Digital	0 & 3 Volts	RT-IHU	Umbilical/Sys	Serial Transmit Channel; ASYNC, Mark High	Y
28	Available	SPI1_SS	Digital	0 & 3 Volts	IHU	RX/TX	SPI1 Slave Select to RX/TX Card's TLM Modulator IC for register access	Legacy Only
29	Available	[Available]						
30	Available	PB_ENABLE	Digital	0 & 3 Volts	IHU	RX/TX	LT User Passband Transmission Enable Signal	Y
31		ALERT Inhibit	Digital	0 & 3 Volts	IHU	CIU	Allows IHU to cycle alert buzzer on the CIU	Y
32	Available	TX_PWR_FWD	Analog	0 to 3 Volts	RX/TX	LIHU	Power Amplifier (FORWARD) Transmit Power	Legacy Only
33	Available	Available						
34	Available	CMD_SERIAL_DATA	Digital	0 & 3 Volts	ICR	LIHU	Software Commands Serial Data Stream	Legacy Only
35	Available	Available						
36	Available	I2C1 Reset	Digital Active Low	0 & 3 Volts	IHU	Subsystems	Pulling this low either resets or power cycles all I2c1 devices	Y
37		I2C2_SCK	Digital	0 & 3 Volts	IHU	ICR	I ² C Standard Bus #2 Clock (Bidirectional): IHU Master and ICR TLM Mux slave	Y
38	Available	I2C2 Reset	Digital Active Low	0 & 3 Volts	IHU	Subsystems	Pulling this low either resets or power cycles all I2c2 device	Y
39		I2C2_SDA	Digital	0 & 3 Volts	IHU	ICR	I ² C Standard Bus #2 DATA (Bidirectional): IHU Master and subsystem slaves	Y
40		TLM_ENABLE	Digital	0 & 3 Volts	IHU	RX/TX	Enable Telemetry and/or Experiment Data transmission on the TLM Downlink channel	Legacy Only
41		CANH	Digital	2.5 or 4 V	RT-IHU & Sys	RT-IHU & Sys	GOLF-Tee System CAN Bus High Signals; 120 ohm termination	*
42	Available	MODEM_CXR_VALID	Digital	0 & 3 Volts	ICR	IHU	ICR CMD Channel Modem CXR valid; High = valid command data detected on CMD channel (gated by RSSI level)	Legacy Only
43		CANL	Digital	2.5 or 4 V	RT-IHU & Sys	RT-IHU & Sys	GOLF-Tee System CAN Bus High Signals; 120 ohm termination	*
44	Available	Available						
45	Available	Available						
46	Available	Available						
47	Available	Available						
48	Available	Available						
49		RT-IHU 1 Console Tx	Digital	Digital	RT-IHU	CIU	RT-IHU Console coming to CIU via IHU	N
50	Available	Available						
51		RTIHU 1 Console Rx	Digital	Digital	RT-IHU	CIU	RT-IHU Console coming to CIU via IHU	N
52	Available	TX_PWR_RFLT	Analog	0 to 3 Volts	RX/TX	ICR	PA (REFLECTED) Transmit Power; carried by Fox Bus to ICR card's ADC/MUX and then on to the IHU via I2C bus (Pin 39)	Legacy Only
53		UMBILICAL_PWR	Digital	0 & 3 Volts	CIU	IHU	High = running on Umbilical Power	N
54		RT-IHU 2 Console Tx	Digital	0 & 3 Volts	CIU	RTIHU	RT-IHU Console coming to CIU umbilical	N
55	Available	[Available]						
56		RTIHU 2 Console Rx	Digital	0 & 3 Volts	RTIHU	CIU	RT-IHU Console coming to CIU umbilical	N
57		V _{system}	Bus Power	6 VDC	CIU	ALL	Main Power Bus, lightly regulated for Point of Delivery (POD)	
58		V _{system}	Bus Power	6 VDC	CIU	ALL	Main Power Bus, lightly regulated for Point of Delivery (POD)	
59		V _{system}	Bus Power	6 VDC	CIU	ALL	Main Power Bus, lightly regulated for Point of Delivery (POD)	
60		V _{system}	Bus Power	6 VDC	CIU	ALL	Main Power Bus, lightly regulated for Point of Delivery (POD)	

= pin assignments dictated by "Legacy (Fox) cards"

GOLF-Tee Bus Lines

Change log

- V1.0 Add sensor power/Reset for each I2c line
 Add new page for I2c and SPI bus uses
 Add LIHU Console serial lines
- V1.1 Add serial and CAN to Data Bus uses
- V1.2 Swap LIHU console and CAN bus pins
- V1.3 Fix LIHU-only first all IHU lines.
- V1.4 Remove separation switch lines + missed one discrete deploy line, no sensor power, just reset on pin 38
- V1.5 Misunderstanding. 36 and 38 each reset a separate I2c bus

Notes

* -- Should be switched so it is driven by Active RT-IHU, but is never disconnected totally from the bus



NOTE: BLACKED OUT CELLS CONTAIN REDACTED INFORMATION (ITAR, NDA, PROPRIETARY, OR COMMAND/CONTROL)

Telemetry Data for Golf-Tee -- V0.1

Name	Type	Range	Units	Bits	Source Board	Source Device	Notes
CIU Panel/CSS Info							
-X Fixed Panel Volts	ADC	TBD	Volts	12	CIU	AD57828 I2c	
+X Center Panel Volts	ADC	TBD	Volts	12	CIU	AD57828 I2c	
+X-Y Panel Volts	ADC	TBD	Volts	12	CIU	AD57828 I2c	
+X+Y Panel Volts	ADC	TBD	Volts	12	CIU	AD57828 I2c	
-X Fixed Panel Temp	ADC	TBD	Volts	12	CIU	AD57828 I2c	
+X Center Panel Temp	ADC	TBD	Volts	12	CIU	AD57828 I2c	
+X-Y Panel Temp	ADC	TBD	Volts	12	CIU	AD57828 I2c	
+X+Y Panel Temp	ADC	TBD	Volts	12	CIU	AD57828 I2c	
+X-Y Panel Deploy Sense Primary	Boolean	True/False		1	CIU	PIC CAN Bus	
+X+Y Panel Deploy Sense Primary	Boolean	True/False		1	CIU	PIC CAN Bus	
UHF Tx1 Deploy Sense Primary	Boolean	True/False		1	CIU	PIC CAN Bus	
UHF Tx2 Deploy Sense Primary	Boolean	True/False		1	CIU	PIC CAN Bus	
VHF Rx Deploy Sense Primary	Boolean	True/False		1	CIU	PIC CAN Bus	
Multiband Rx Deploy Sense Primary	Boolean	True/False		1	CIU	PIC CAN Bus	
Deorbit Device Sense Primary	Boolean	True/False		1	CIU	PIC CAN Bus	
+X-Y Panel Deploy Sense Secondary	Boolean	True/False		1	CIU	PCA9539 I2c	
+X+Y Panel Deploy Sense Secondary	Boolean	True/False		1	CIU	PCA9539 I2c	
UHF Tx1 Deploy Sense Secondary	Boolean	True/False		1	CIU	PCA9539 I2c	
UHF Tx2 Deploy Sense Secondary	Boolean	True/False		1	CIU	PCA9539 I2c	
VHF Rx Deploy Sense Secondary	Boolean	True/False		1	CIU	PCA9539 I2c	
Multiband Rx Deploy Sense Secondary	Boolean	True/False		1	CIU	PCA9539 I2c	
Deorbit Device Sense Secondary	Boolean	True/False		1	CIU	PCA9539 I2c	
CoarseSunSensor1	ADC	TBD	?	12	CIU	AD57828 I2c	
CoarseSunSensor2	ADC	TBD	?	12	CIU	AD57828 I2c	
CoarseSunSensor3	ADC	TBD	?	12	CIU	AD57828 I2c	
CoarseSunSensor4	ADC	TBD	?	12	CIU	AD57828 I2c	
CoarseSunSensor5	ADC	TBD	?	12	CIU	AD57828 I2c	
CoarseSunSensor6	ADC	TBD	?	12	CIU	AD57828 I2c	
CoarseSunSensor7	ADC	TBD	?	12	CIU	AD57828 I2c	
CoarseSunSensor8	ADC	TBD	?	12	CIU	AD57828 I2c	
Power Info							
CIU Over Current	Boolean	True/False		1	CIU	FPF2004 PIC CAN	
LIHU Over Current	Boolean	True/False		1	LIHU	FPF200x	
RTIHU Primary Over Current	Boolean	True/False		1	RTIHU Primary	FPF200x	
RTIHU Secondary Over Current	Boolean	True/False		1	RTIHU Secondary	FPF200x	

RT-IHU Info

RTIHU Primary Board Temp	Digital	-55C/150C	Degrees C	16	RTIHU Primary	MAX31725 I2c
RTIHU Secondary Board Temp	Digital	-55C/150C	Degrees C	16	RTIHU Secondary	MAX31725 I2c
Error info from RT-IHU (tbd)	TBD	TBD		TBD		
DCT Info (RSSI, etc as available)	Integer	0/255		8	Primary RTIHU	Internal state
DCT Cmd Count Primary	Integer	0/255		8	Secondary RTIHU	Internal state
DCT Cmd Count Secondary	Coded Int	0/0 to 65535/33554434	Reset/Seconds	41	LIHU	Internal State
Time Last Primary DCT Cmd	Coded Int	0/0 to 65535/33554435	Reset/Seconds	41	LIHU	Internal State
Time Last Secondary DCT Cmd						

RF Matrix Info

RF Matrix State	Coded Int	Lband,Cband,Sband		8	RF Switch	MAX7320 I2c
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Only 3 mutually exclusive values, but send all 8 bits just in case

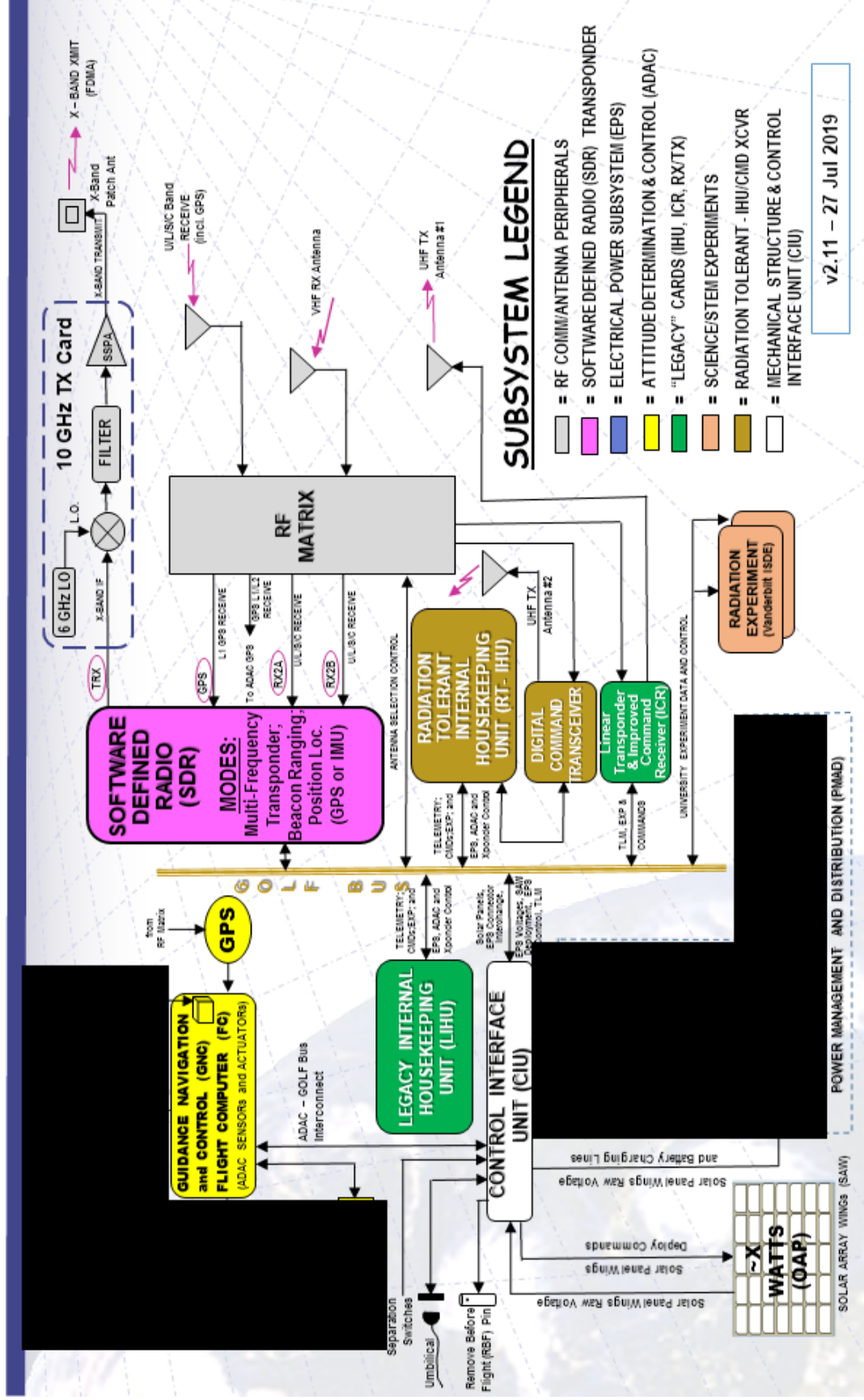
SDR Info

SDR Info	TBD			8		
SDR Mode	Coded Int			8	SDR/Active IHU	Internal State
GPS Current Week Number	Integer	0/1024	Week number	10	SDR	CAN
GPS Current Time of Week	Integer	0/403199	Seconds	19	SDR	CAN

Other info available from SDR-temp? Power?

Ragnrok Info

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Date: September 1, 2019

Version: 1.3

AMSAT *GOLF-TEE* Satellite

Concept of Operations

1 Introduction

The AMSAT Fox-1 satellites, Fox-1A through Fox-1E, were the first CubeSat projects undertaken by AMSAT. Within a 1U satellite form factor, they provide an FM repeater function, except for Fox-1E which provides a Linear Transponder. The Fox-1 satellite family orbits were intended to provide wide geographical coverage allowing amateur radio operators to communicate over substantial distances using just a handheld transceiver (i.e. a walkie-talkie) and a small handheld antenna. This type of satellite operation is often referred to as the EasySat mode due to its simplicity. It is extremely valuable in providing an introduction to satellite communications and is often used for demonstrations given at schools, to scouting organizations, and at amateur radio publicity events. In addition, the Fox-1 series CubeSats hosted several experiment payloads provided by educational institutions such as Vanderbilt University ISDE, Penn State Erie, Virginia Tech, and the University of Iowa. In so doing, they inspired other institutions to seek opportunities with us. Currently, AMSAT has four Fox-1 spacecraft on orbit and one other manifest for launch in late 2019.

The GOLF (Greater Orbit, Larger Footprint) series of 3U CubeSats will be the logical successor to the Fox-1 program and builds on some of the original concepts initially envisioned for an earlier proposed “Fox-2” series. Now, building on the success of the Fox-1 program, GOLF will continue orbiting a series of satellites to fulfill our vision of “keeping amateur radio in space” as well as to challenge our engineers by moving to a larger platform that will provide more power and volume for radios and antennas as well as experiments. Attitude control will be incorporated providing the ability to point high gain antennas, maximize power generation, mitigate thermal conditions, and provide for propulsion.

This Concept of Operations addresses an opportunity to “jump start” the GOLF series of 3U CubeSats through the availability of hardware, software, and a launch opportunity resulting from the partnership between AMSAT and Ragnarok Industries in pursuit of the Heimdallr 6U CubeSat for the NASA Cube Quest Challenge. The spacecraft hardware and software developed by Ragnarok and the radio technology developed by AMSAT for that project form the basis for this project. By adding a spaceframe and solar panels developed by AMSAT, experiments provided by Vanderbilt University ISDE, and other radio technology under development by AMSAT’s Advanced Satellite Communications and Exploration of New Technology (ASCENT) initiative, AMSAT has the opportunity to advance our knowledge of the subsystems desired for the GOLF program at a relatively low cost.

AMSAT’s submitted proposal to the NASA ELaNa¹ program for a low-cost launch of this satellite was accepted with a launch expected in the late 2020 or early 2021 time frame. AMSAT-NA believes this project will nicely address the goals and objectives of the NASA program and provide the initial work necessary to enable a return to higher orbit advanced communications technology missions benefitting radio amateur operators and experimenters worldwide.

¹ Announcement of CubeSat Launch Initiative, Solicitation Number NNH17ZCQ001O, August 3, 2017, NASA HQ Acquisition Branch, Code 210.H, Greenbelt, MD 20771. Information on the NASA Educational Launch of NanoSatellites (ELaNa) program can be found on the NASA web site:
http://www.nasa.gov/offices/education/centers/kennedy/technology/elana_feature.html

1.1 Document History

DATE	VERSION	AUTHOR	SUMMARY OF REVISION CHANGES
October 16, 2017	V1.0	G. Buxton	Initial draft
October 27, 2017	V1.1	G. Buxton	Editorial changes, i.e., typos, acronym expansions, additional clarifying information, etc.
November 18, 2017	V1.2	G. Buxton	Align and order goals, clarify information
March 3, 2018	V1.21	G. Buxton	Add author field to document history
September 1, 2019	V1.3	E. Skoog	Proposal acceptance updates and revised Operational Mode descriptions

1.2 Program Goals and Objectives

AMSAT's *GOLF-TEE* satellite is intended to:

- Provide an opportunity to work with and improve our knowledge of 3-axis satellite active and passive Attitude Determination And Control (ADAC),
- Provide a platform to test and demonstrate low cost radiation event fault tolerant IHU and satellite command radios,
- Provide a platform to aid in the development of a 3U CubeSat spaceframe and deployable solar panel designs that can serve a variety of missions,
- Provide an on-orbit amateur radio transponder to allow communications between amateur radio operators,
- Provide a platform to test and demonstrate “Five and Dime” (5 GHz uplink / 10 GHz downlink) technology for amateur radio communications using AMSAT Ground Terminal design-based ground stations,
- Provide a platform to test and demonstrate software defined radio (SDR) HF, VHF, UHF and microwave transponder technology for amateur radio communications using existing amateur satellite ground stations,
- Continue to build relationships with universities, including student development of satellite components and subsystems, and
- Provide a platform to test and demonstrate software needed by the AMSAT Operations Team to successfully operate a 3-axis stabilized satellite in orbit.

1.3 Mission Overview

The primary mission of the *GOLF-TEE* satellite is to:

- Provide the hardware and software systems necessary to demonstrate and gain knowledge of 3-axis ADAC of a 3U satellite for purposes such high gain antenna pointing, propulsion, collision mitigation, and de-orbiting capabilities and,
- Test and demonstrate low cost radiation event fault tolerant IHU and satellite command radios for improved reliability of satellite control in Low Earth Orbit and Medium Earth Orbit.

The secondary mission of the satellite is to provide one or more amateur radio transponders demonstrating communications capability that can be accessed using AMSAT Ground Terminal design-based ground stations or relatively simple ground station equipment such as low power portable transceivers paired with small, handheld beam antennas. The satellite communications transponders will employ SDR-based radios demonstrating techniques desired for “Five and Dime” digital/microwave systems and linear transponder

functions as found in the amateur radio VHF and UHF satellite bands.

The radio communications capabilities of the satellite will be used to uplink control commands for operation of the satellite, particularly ADAC, as well as operation of the radios and experiment(s) as needed. Communications capabilities will also downlink data necessary for proper ADAC as well as data collected from the experiment(s) to ground stations.

1.4 Scope

The scope of this Concept of Operations (CONOPS) document describes the GOLF satellite system and how it will be used. This is not a requirements document but provides operational context that will be helpful in developing and understanding system requirements and creating interface specifications.

2 System Description

2.1 Spacecraft

The initial project to be executed under the GOLF program will be called GOLF-TEE, where the “TEE” indicates a ‘technology exploration environment’ development satellite expected to exhibit the following features and characteristics:

- 3 Unit CubeSat form factor
- 500 km or greater orbit
- 3-axis Attitude Determination And Control (ADAC)
- Deployable solar panels
- Experiment payload(s)
- “Five and Dime” digital transponder
- VHF/UHF analog transponder
- 400 mW minimum RF output power
- Deployable antennas
- Rechargeable battery to support operation during eclipse periods
- Proprietary scheme for command control uplink
- Separate dedicated channel for downlinking telemetry and experiment data

This list is preliminary and subject to change.

NOTE: This CONOPS is not the controlling document for satellite technical specifications.

2.2 Telemetry and Experiment Data

Telemetry data consists of internally monitored satellite subsystem points that provide a measure of the satellite’s attitude, status, and health. The satellite will autonomously and regularly measure these points and transmit the data provided on the telemetry downlink. Experiment data will be collected as per the requirements of the experiment and will be stored and/or transmitted on the downlink as needed.

Additionally, Whole Orbit Data (WOD) will be collected for the above measurements and transmitted to ground.

Telemetry and experiment data will be transmitted in the clear allowing any ground station to receive it. The information needed to demodulate and decode the downlink signal will be placed in the public

domain. An open-source, software package for decoding the telemetry and experiment data will be made available by AMSAT.

2.3 Satellite Commands

The satellite will accept commands from AMSAT vetted control stations. These are used to control the attitude, modes, and operation of the satellite. Commands are intended to be limited to use by authorized stations only. Private codes and/or unpublished information will be used to command the satellite.

2.4 Ground Control Stations

Commands will be executed by way of the VHF or UHF amateur radio satellite band, and may be tested on the 5 GHz C-band uplink. It is expected that control stations will not require any specialized radio equipment/hardware, but may need to be able to generate higher radiated power levels than typical for users in order to gain control of the satellite. In order to command the satellite, specialized software will be required. This software will be developed and provided by AMSAT as part of the satellite development effort.

2.5 Amateur Radio User Stations

This satellite will employ radio standards commonly used on the amateur radio VHF and UHF bands for the analog transponder and will not require any specialized equipment for normal operation on that transponder. A low power transmitter/receiver pair for duplex operation, with a small hand-held Yagi antenna, should be considered a typical user station for the VHF/UHF analog transponder. Operation with fixed, omni-directional antennas should also be possible with typical amateur radio base and mobile transceivers.

The C/X band “Five and Dime” transponder may eventually use digital techniques being developed for the Phase 4B and HEO AMSAT Ground Terminal. Elements of the AMSAT Ground Terminal for transmitting and receiving will be available either in kit form or via AMSAT Ground Terminal documentation and commonly available components to provide the ability to operate through the “Five and Dime” transponder.

3 Operational Modes

Specifying operational modes is central to the design of a system to ensure it functions as required. Two useful (paraphrased) definitions of modes are:

*A **mode** represents a distinct operating capability of a system during which some or all of its functions may be performed to a full or limited degree. Modes may be considered as the highest level functions of a system.²*

*A **mode** is an abstract label applied to a collection of a system’s operational capabilities and activities focused on satisfying some of the objectives of a specific operational phase.³*

Often there is confusion between specifying a system’s operational modes and its underlying functions or states. These terms have different meanings. Operational Modes are based on the necessary functions and capabilities a system must exhibit. The definition of a function is:

² D. Buede, *The Engineering Design of Systems: Models and Methods*. Wiley, 2 ed., February 2009

³ C. Wasson, *System Analysis, Design, and Development: Concepts, Principles, and Practices*. Wiley, 1 ed., March 2006.

A **Function** of a system is defined as a specific/discrete action (or series of actions) necessary to support an Operational Mode; that is, system tasks supporting desired operational behavior.⁴

At a lower, realizable design level, states are a physical representation of a system's operational modes and functions expressed by a set of definitive state variables. The definition of a state is:

The **State** of a system is defined as a static snapshot of a set of metric variables needed to fully describe a system's capabilities to perform the required functions. Specifically, the state of a system is the list of variables, aka state variables, or values at a specific point in time.²

In determining the operational modes of a system, it is desirable that the set of modes be defined as mutually exclusive. That is, a system's operational architecture should be defined such that its execution can be described by only one mode executing at any point in time. To this end, to ensure distinct operational separation of modes, it is convenient to identify functions that may support several different modes. Three examples of such multi-mode supporting functions are:

- 1.) **Umbilical Control Function** - When the GOLF-Tee satellite is under development and partially or completely integrated on-the-bench, a controlling umbilical cord is normally plugged in and power may be supplied externally via a charging cable. A "Remove Before Flight" (RBF) pin is not inserted in the satellite's receptacle, and internal satellite On Board Computer (OBC) program execution may be over-ridden (preempted) by umbilical cable insertion and/or specific terminal commands. Umbilical controlled satellite *functioning* is not considered an "OPS MODE" since control actions with an attached umbilical cord and an external terminal program can take precedence over any operational mode actions. This is a particularly beneficial when verifying the performance of Operational Modes during development and testing.
- 2.) **Attitude Determination and Control (ADAC) Function** – When the satellite is on-orbit and is acquiring sufficient solar energy to operate in a positive power budget, the ADAC Subsystem *functions* continuously to maintain maximum power generation, thermal management attitude, and optimum antenna pointing. Such 3-axis stabilization actions are considered a 'normal' operating function and can execute in support of several Operational Modes as determined by the controlling Ground Station(s).
- 3.) **Ground Control Command Function** – After initial deployment, subsequent to antenna deployment, the satellite will continuously monitor the command uplink frequency for any commands from AMSAT authorized Ground Control Stations. Only those stations can command the operation of the various satellite subsystems at ANY time, regardless of the operational mode in effect.

The following paragraphs describe the intended Operational Modes of AMSAT's GOLF-Tee satellite. Specifically, they define three (3) modes exhibited by the spacecraft during pre-deployment and initial on-orbit functioning. The remaining five (5) operational modes define on-orbit "*normal*" and degraded mode operations.

3.1 Dispenser Secure Mode

This mode represents the satellite's operational condition after it has been integrated into a launch dispenser. The "Remove Before Flight" (RBF) pin has been pulled, but either one of the (actuated) satellite's redundant deployment separation switches prevents any power-up operations. If the umbilical and power charging ports of the satellite are accessible while it is in a dispenser, a test umbilical and power charging cable can be connected to a port on the satellite to allow limited subsystems to be powered, the battery to be charged, and diagnostic tests to be run. Once the satellite has been integrated into its dispenser and launch acceptance tests have been run, the only way to know if a satellite is still

⁴ B. Blanchard, W.J. Fabrycky, *Systems Engineering and Analysis*. Prentice Hall, 5th ed., April 2009.

functional is via these diagnostic tests. Therefore, the diagnostics should be as thorough as possible given the constraints of the dispenser environment.

3.2 Initial Orbit Mode

When the satellite is released into its initial orbit by the dispenser, the deployment separation switches on the satellite revert to their non-actuated (normal open) state signaling the satellite to initiate a set of basic “wake-up” actions. Specifically, the absence of activation prevention signals will cause the Electrical Power Subsystem (EPS) to enable battery discharge regulation. Stored battery energy will then facilitate boot-up of the EPS processor, along with the satellite’s On Board Computers (OBC). After boot-up, the OBCs will run Power-On-Self-Tests (POST) and verify they are communicating with each other and able to recognize and switch main control responsibilities. Then, the legacy OBC (see System Requirements Specification, § 3.5.1), if capable, will assume primary command of the satellite. The OBC, as required by the CubeSat Design Specification, will time a 50 minute interval and then execute deployment actions in the following sequence:

- a. UHF transmit monopole antenna no. 2 dedicated to the Linear Transponder’s transmitter,
- b. UHF transmit monopole antenna no. 1 dedicated to the RT-IHU’s transmitter,
- c. VHF receive monopole antenna shared by both of the satellite’s OBCs,
- d. Solar Panel Array Deployable Wing no. 1
- e. Solar Panel Array Deployable Wing no. 2
- f. Multi-band Planar Disc Antenna

Once the antenna sensor has verified successful deployment of the UHF transmit antenna dedicated to the in-control OBC, on-orbit “beacon” transmissions will be initiated. Beacon transmissions herald initial “I’m Alive” on-orbit identification and will include satellite orientation (attitude) and battery charge status data for AMSAT ground station monitoring, i.e., the satellite’s initial most critical status data transmitted via low duty cycle RF transmissions for assessment of the health and status of the satellite immediately after deployment. Concurrent with beacon telemetry being transmitted, the EPS will initiate power point tracking (PPT) of received solar panel generated power from all deployed and fixed solar panels to support battery charge regulation.

3.3 De-Tumble Mode

Deployment from the dispenser will induce partial spin in the satellite’s 3-axes. Following Initial Orbit Mode autonomous power up actions, the satellite will continue to transmit beacon message health and status telemetry data. When the controlling OBC detects that the power budget is adequate, it will command the Attitude Determination and Control (ADAC) subsystem to power up its Flight Computer (FC), Magnetorquers, and Coarse Sun Sensors (CSS). These actions denote the initiation of De-tumble Mode. This mode is entirely controlled by the ADAC subsystem FC. De-tumble Mode execution will utilize attitude determination via the satellite’s CSS and Inertial Measurement Unit (IMU) gyro information to effect magnetorquer actuations to stabilize the satellite’s orientation over a period of time. While the satellite’s initial spinning attitude is being stabilized through De-Tumble Mode actions, the satellite’s in-control OBC will continue to provide beacon telemetry data transmissions to update AMSAT ground control stations re the battery packs’ State of Charge (SoC). Receipt of the SoC telemetry data signifies the start of on-orbit collaborative commissioning by the AMSAT OPS and ENG team.

Upon commissioning team determination that a successful state of de-tumbling has been achieved, the team will begin execution of a scripted “In Orbit Checklist” by transmitting a command to initiate the Attitude Control function. Initial Attitude Control actions will maintain power control/saving actions to ensure enough power is available to allow activation of the ADAC’s attitude determination sensors and actuators and initiate telemetry transmissions identifying attitude determination and actuator adjustment actions (e.g., startracker picture data, reaction wheel performance, IMU readings, etc.). That is, if data

indications are sufficient, e.g., the solar panels are providing power point tracked energy to the battery packs and there is adequate power subsystem energy available to support initial attitude maneuvering, the commissioning team will uplink a command to the ADAC Flight Computer (FC) to power up the ADAC's StarTrackers and Reaction Wheels. With this complete set of attitude sensors and actuators, the FC will then begin to execute its attitude control system (ACS) algorithms and complete its Sun-Pointing maneuvers. After achieving sufficient Sun-Pointing position, with adequate mission supporting battery pack energy, the AMSAT commissioning team may declare the satellite ready for amateur radio communications and experiment use. *[NOTE: Once the satellite has been stabilized for primary mission execution, the Attitude Determination and Control function will always continue to execute "background" processing actions, UNLESS inhibited by an OBC or AMSAT Ground Control Station command due to an extremely low power situation or other anomalous conditions as determined by the command team.]*

3.4 Transponder Mode

In Transponder Mode, signals appearing on the uplink(s) will be repeated on the downlink(s) for the enabled transponder(s), frequencies, and times as commanded by AMSAT authorized Ground Control Stations. In this mode, amateur radio user stations worldwide are permitted to use the satellite for general communications. While in Transponder Mode, GOLF-Tee will be capable of simultaneously transmitting telemetry and experiment data on a separate telemetry downlink frequency so as not to interfere with transponder communications.

GOLF-Tee will feature two separate, independent transponders, (1) an experimental Software Defined Radio (SDR) controlled digital transponder, and (2) a flight proven analog Linear Transponder (LT).

3.4.1 SDR Transponder

GOLF Tee's Software Defined Radio (SDR) subsystem provides an advanced communications technology contrast to AMSAT's legacy LT's analog transponder. The SDR's "communication modes" (*comm modes*) will be able to use input frequencies covering the IARU amateur satellite service allocated bands of 70 cm (435-438 MHz), L-Band (1,260-1,270 MHz), S1-Band (2,400-2,450 MHz), C-Band (5,650-5,670 MHz), and any experimental or emergency frequency between 144 and 6,000 MHz. The SDR's output will always be at X-band in the frequency range of 10,450 to 10,500 MHz. Exact frequencies are TBD based on IARU coordinated allocations.

All SDR comm modes will be enabled through commands from AMSAT authorized ground control stations. Uplink commands will designate the desired comm modes to be executed from SDR memory stored firmware programs. The following sections summarize the seven (7) unique comm modes the SDR provides, viz., 3 data downloads, 4 transponder programs, and possible additional comm modes.

3.4.1.1 Beacon Comm Mode 1

This comm mode consists of one CW ID stream at approximately 10 wpm, a CW lock tone to enable better ground locking of the Doppler, and a wideband data channel. The data channel will be a GMSK modulated signal. The data channel download rate will be determined by an uplink command (e.g., ***beacon1 -128.e3*** for a 128 kHz data rate).

3.4.1.2 Beacon Comm Mode 2

This comm mode consists of one CW ID stream at approximately 10 wpm, a CW lock tone to enable better ground locking of the Doppler, and a wideband data channel. The data channel will be a BPSK modulated signal. The data channel download rate will be determined by an uplink command (e.g., ***beacon2 -128.e3*** for a 128 kHz data rate).

3.4.1.3 Beacon Comm Mode 3

This comm mode consists of one CW ID stream at approximately 10 wpm, a CW lock tone to enable better ground locking of the Doppler, and a wideband data channel. The data channel will be an OFDM modulated signal. The data channel download rate will be determined by an uplink command (e.g., *beacon3 -256.e3* for a 256 kHz data rate).

3.4.1.4 Multi-Use Comm Mode 4

This comm mode consists of one CW ID stream at approximately 10 wpm and a CW lock tone to enable better ground locking of the Doppler. This comm mode will provide 4 transponder (bent pipe) channels, each approximately 18 kHz wide with each channel's center frequency separated 25 kHz from the adjacent channel's center frequency. Each channel shall exhibit AGC and squelch. Additionally, a single wideband 100 kHz bandwidth bent pipe channel will be provided. RF output power will be shared between all channels equally. Mixed mode operation will be possible since no channels are subject to demodulation processing.

3.4.1.5 Multi-Use Comm Mode 5

This comm mode consists of one CW ID stream at approximately 10 wpm and a CW lock tone to enable better ground locking of the Doppler. This comm mode will provide 5 transponder (bent pipe) channels, each approximately 18 kHz wide with each channel's center frequency separated 25 kHz from the adjacent channel's center frequency. Each channel shall exhibit AGC and squelch. Additionally, a single wideband 100 kHz bandwidth bent pipe channel will be provided. RF output power will be shared between all channels equally. Mixed mode operation will be possible since no channels are subject to demodulation processing.

3.4.1.6 Multi-Use Comm Mode 6

This comm mode consists of one CW ID stream at approximately 10 wpm and a CW lock tone to enable better ground locking of the Doppler. This comm mode will provide 19 transponder (bent pipe) channels each approximately 18 kHz wide with each channel's center frequency separated 25 kHz from the adjacent channel's center frequency. Each channel shall exhibit AGC and squelch. The CW ID stream will be part of the 19th transponder channel.

3.4.1.7 Single-Use Comm Mode 7

This comm mode consists of one CW ID stream at approximately 10 wpm and a CW lock tone to enable better ground locking of the Doppler. This comm mode will provide 1 transponder (bent pipe) channel approximately 40 kHz wide with AGC and squelch. This mode will be tuned to the GOLF-Tee Linear Transponder's UHF (70 cm band) downlink frequency. Hence this comm mode enables UHF/x-band 'cascaded' transponding simultaneously with LT V/u transponding of the same VHF uplinked signal(s).

3.4.1.8 Additional Comm Modes

Availability and capabilities of any future comm modes developed are TBD based on development testing, integration and frequency authorization. 50 MHz bandwidth bent pipe comm modes, along with de-modulation/modulation of voice and data may be feasible.

3.4.2 Linear Transponder (LT)

AMSAT's Linear Transponder will provide simultaneous multi-channel communications to support multiple CW and SSB contacts. The design of the transponder includes state-of-the-art integrated circuit components to provide robust communications performance, while minimizing

size, weight and power. The analog LT functions as an inverting V/u (bent pipe) transponder. Consequently, operator uplink transmissions will require generation of VHF (2 meter) SSB/CW amateur radio signals and downlink signal capture will require reception of UHF (70 cm) SSB/CW signals. A separate frequency 1200 bps BPSK modulated channel will be dedicated to downlinking GOLF-Tee telemetry and experiment data.

3.5 Telemetry Mode

Telemetry Mode provides transmissions, with a specific duty cycle commanded, of particular satellite telemetry data while inhibiting all communications traffic transponding, i.e., in Telemetry Mode, user signals appearing on the transponders' uplink(s) will not be repeated on the downlink(s). Although the 'normal low speed' Telemetry Mode transmissions will be provided by the Linear Transponder's dedicated telemetry downlink, high speed telemetry transmissions may be supported by the SDR's high data rate comm modes (see 3.4.1.1 – 3.4.1.3), and/or the RT-IHU's DCT high speed downlink rates. Telemetry Mode is used extensively when it is desired to monitor the health and status of the satellite, or to support dedicated high speed downlinking of experiment data, including camera pictures.

3.6 Transmit Inhibit Mode

In order to meet FCC requirements, the satellite will accept a Ground Control Station command to inhibit all transmissions regardless of the operating mode in effect at the time. Once inhibited, the transmitter(s) will not be activated under any autonomous conditions, but the satellite will continue to monitor the command channel uplink for direction. An AMSAT authorized Ground Control Station must send a properly authenticated command to remove Transmit Inhibit and re-enable the transmitter(s). Transmit Inhibit must be executed via a satellite hardware control action affecting each transmitter, and may also be enabled via software actions.

3.7 Safe Mode

Safe Mode is a protective mode of operation that is initiated by Ground Control Station command when desired, or automatically (**Auto Safe Mode**) by satellite OBC and EPS subsystem actions when certain parameters are met that imply a possibly harmful state of satellite operation or subsystem functions. The intent of Safe Mode is to secure the satellite in a power positive, thermally benign state to allow time for proper start-up actions, and/or troubleshooting and recovery from operational anomalies. Safe Mode provides for the transmission of telemetry messages containing detailed data for satellite status, troubleshooting, and problem determination. Safe Mode telemetry transmissions occur at a special RF power output level and duty cycle. While in Safe Mode, all transponding and experimentation are inhibited, but continuous attitude correction actions via ADAC control of the Magnetorquers, Coarse Sun Sensors, Inertial Measurement Units, Reaction Wheels, and Startrackers are allowed IF on-board energy generation/storage is sufficient.

3.8 Degraded Mode

Degraded Mode operations address a select set of potential failure scenarios via mitigating actions designed to extend the useful life of the satellite. An experiment may or may not be permitted to continue operations under some failure scenarios. The list of some of the potential failure scenarios envisioned and the pre-planned actions are below:

3.8.1 Battery Failure

If the battery deteriorates or fails completely, including shorted or open cells, the satellite will continue to operate directly from its solar panels' power while in the sun. In eclipse, the satellite may power down. When back in sunlight, the satellite will automatically reenter its last operational mode with the same in-command OBC, if functional.

3.8.2 On Board Computer (OBC) Failure

Any one of the GOLF-Tee CubeSat's three OBCs is capable of functioning as the main satellite Control and Data Handling (C&DH) processor and therefore regulate the satellite subsystems' functions. The three main OBCs are the Legacy Internal Housekeeping Unit (LIHU) and the Dual-MCU Radiation-Tolerant IHU (RT-IHU). The RT-IHU's primary and secondary processors provide complete redundancy. In the event NONE of these processors are operational, the satellite will default to operate in a (pseudo) Transponder Mode where the SDR Transponder will revert to L/x and the Linear Transponder will operate in its normal V/u transponder mode – both autonomously without any ground control station commanding. In the event of such complete OBC failure, no satellite telemetry or experiment data will be available for downlinking.

3.8.3 Reaction Wheel Failure

Should 1 of the 4 reaction wheels fail, the remaining 3 reaction wheels allow for momentum storage in 3 axes. Severe failure occurs when more than 2 wheels or their regulated 12 volt power line fails. In this event, although there is no momentum storage capability, the magnetorquers will still allow for coarse attitude pointing.

3.8.4 Startracker Failure

Should 1 of the 2 startrackers fail, the remaining startracker will still provide attitude determination.

3.8.5 Coarse Sun Sensor (CSS) Failure

Should 1 of the 8 coarse sun sensor photodiodes fail, the remaining 7 photodiodes are used to infer the Sun vector, albeit with a larger uncertainty. The cause of CSS failure may be its transimpedance amplifier (TIA) or the photodiode itself. A severe failure occurs when the Analog-to-Digital Converter (ADC) fails, thus eliminating readings from all CSSs.

3.8.6 EPS Power Generation Failure

Should 1 of the 4 Peak Power Tracker (PPT) units fail, the remaining 3 shall continue delivering peak power from their respective solar panels. Satellite Power budget is reduced, yet conditions still permit degraded mode operation. Minimal operation occurs when 3 out of 4 PPTs fail, and critical failure occurs when all PPTs have failed. Each PPT is independently powered directly from the solar panel raw voltage.

3.8.7 Inertial Measurement Unit (IMU) Failure

The ADAC flight computer features an onboard 9-axis MEMS-type InvenSense IMU and separately features a more precise 6-axis EPSON IMU. Should either of these IMUs fail, the remaining IMU allows for continued operation.

3.8.8 Power Distribution 3V3 Voltage Regulator Failure

Should the 3.3V regulated voltage line fail, all devices powered from this voltage line, including those of the ADAC fail. Therefore, in order to mitigate this severe scenario, the EPS design shall configure the 6th power distribution converter to provide 3V3 as a redundant unit to the internal 3V3 line.

3.8.9 Power Distribution 12V and 6V Voltage Distribution Failure

The EPS provides independent/redundant + 12 V regulated voltage lines for AMSAT prime power. These lines in turn supply input power to 2 independent/redundant + 6 V Buck Converters. This results in load-balancing between TWO INDEPENDENT/REDUNDANT + 6 V prime power feeds to AMSAT's Vsys main power bus. Failure of either power feed, will be detected and result in shutdown of selected satellite capabilities via ground assessment and command while continuing

degraded mode operations utilizing the remaining + 6 V power line.

4 Mission Operations Overview

The AMSAT Operations and Engineering Teams will work together to commission the satellite after launch. Commissioning is required to ensure the satellite is operating nominally or to determine the capabilities of the satellite if nominal operation is diminished. Commissioning will include all specified qualification tests of the ADAC and IHU required to fulfill the goals of the mission. After commissioning, the satellite will be turned over to the AMSAT Operations Team. It is expected the AMSAT Operations Team would then open the satellite for general communications use by any licensed amateur radio station, and perform communications scheduling and required attitude control to maintain desired performance.

As part of ongoing satellite operations, AMSAT Operations and AMSAT Engineering Teams will cooperate in exercising and learning the skills needed for successful attitude control to achieve goals such as maximum antenna gain, minimum or maximum drag collision avoidance techniques, and maximum power (sunlight) positioning. Additionally, cooperation in exercising the radio packages in order to gather data and learn best practices for use in future radio development is expected.

The AMSAT Operations Team will collect and archive all telemetry and experiment data and make it freely available on the Internet.

5 Reference Documents

1. CubeSat Design Specification Rev. 13. by The CubeSat Program Cal Poly SLO available from: http://www.cubesat.org/s/cds_rev13_final2.pdf
2. ITU Radio Regulations, Edition of 2016. available from <http://www.itu.int/pub/R-REG-RR-2016>
3. Launch Services Program, Program Level Poly Picosatellite Orbital Deployer (PPOD) and CubeSat Requirements Document LSP-REQ-317.01 Revision B (from NASA)